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Optics and Plasma Research Department annual progress report for 2004

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Optics and Plasma Research Department
Annual Progress Report for 2004

**Edited by H. Bindslev, J.P. Lynov, C. Pedersen,
P.M. Petersen and B. Skaarup**

**Risø National Laboratory, Roskilde, Denmark
March 2005**

Abstract The Optics and Plasma Research Department performs basic and applied research within three scientific programmes: (1) laser systems and optical materials, (2) optical diagnostics and information processing and (3) plasma physics and technology. The department has core competencies in optical sensors, optical materials, biophotonics, fusion plasma physics, and industrial plasma technology. The department employs key technologies in micro- and nanotechnology for optical systems, temperature calibration, and infrared measurement techniques. The research is supported by several EU programmes, including EURATOM, by Danish research councils and by industry. A summary of the activities in 2004 is presented.

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1. Introduction

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At the beginning of 2004, the department changed name from the “Optics and Fluid Dynamics Department” to the “Optics and Plasma Research Department”. At the same time, the former research programme “Plasma and Fluid Dynamics” changed name to “Plasma Physics and Technology”. These name changes were introduced to give a better reflection of the content of the research projects.

The research in the department is conducted as a combination of science and technology with the following core competencies:

- Optical sensors
    - Light propagation in complex systems
    - Laser-based sensors
    - Diffractive optical components
    - Phase contrast methods
- Optical materials
    - Polymers
    - Laser ablation
    - Holographic storage
    - Light emitting diodes
- Biophotonics
    - Light/tissue interaction
    - Diode laser systems
    - Biosensors
    - Image processing
    - Optical tweezers
    - IR spectroscopy
- Fusion plasma physics
    - Theoretical and numerical plasma physics
    - Millimetre wave diagnostics
- Industrial plasma technology
    - Surface treatment of materials
    - Pollution remediation
    - Sterilisation

The output from the research activities is new knowledge and technology. The users are within industry, research communities and government, and the department is responsible for the Danish participation in EURATOM's fusion energy programme.

For the solution of many of the scientific and technological problems the department employs the following key technologies:

- Micro- and nanotechnology for optical systems
    - Analogue and digital laser recording of holograms
    - Injection moulding of diffractive optical elements
- Temperature calibration and IR measurement techniques
    - Accredited temperature calibration including IR techniques
    - Fourier transform infrared (FTIR) measurements

The department is organised in three scientific programmes:

- Laser systems and optical materials
- Optical diagnostics and information processing
- Plasma physics and technology

In the following sections, the scientific and technical achievements during 2004 for each of these programmes are described in more detail.

2. Laser systems and optical materials

2.1 Introduction

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The research programme on Laser Systems and Optical Materials (LSO) has its main competencies within the areas of laser systems, laser ablation and pulsed laser deposition, biomedical optics and optical sensors, nanotechnology, and light emitting diodes.

We have close collaboration with Danish and foreign universities, research institutes and industry. Nationally, we participate in the Danish Polymer Centre and the Center for Biomedical Optics and New Laser Systems. Moreover, the research programme plays a key role in the Danish Graduate School on Biomedical Optics and New Laser Systems. LSO undertakes significant teaching activities at both the University of Copenhagen and the Technical University of Denmark. Internationally, the research programme participates in the WWW.BRIGHT.EU consortium; the purposes of this consortium are (1) to push the limits of the current laser diode technology towards higher brightness, and (2) to demonstrate applications within, e.g., cancer therapy and telecommunication networks.

Development of new laser systems is an important activity in LSO. We carry out fundamental studies as well as applied research where new industrial lasers are constructed. We are presently developing new and improved laser systems for medical applications, materials processing, printing, rapid prototyping, biotechnology and optical sensing. An important research area is the development of new high-power, tunable semiconductors with high spatial and temporal coherence and their application in second harmonic generation.

The polymer optics activities in LSO are currently involved in the fabrication and replication of diffractive optics, dynamic holographic recording materials, liquid crystalline polymers as well as laser-assisted deposition of transparent coatings (indium tin oxide, ITO) on polymers.

Laser ablation is also performed in LSO with facilities that comprise a vacuum chamber for studying fundamental laser plume properties, a vacuum chamber for thin film production by pulsed laser deposition and a test chamber for production of polymer films. The facilities are based on UV light from an Nd:YAG laser with pulse energies up to 200 mJ at 355 nm.

Nonlinear optics has been a research subject of intense investigation for many years. The field covering the dynamics of optical materials is concentrated on both inorganic and organic materials. Among the inorganic materials the activities have been within photorefractives and semiconductors in which nonlinear effects such as parametric oscillation and amplification, optical phase conjugation and four-wave mixing have been studied.

Finally, light emitting diodes (LED) constitute an important activity in LSO. The activity includes development of new optics for LEDs that can both mix coloured light to white light and spread the light in order to obtain light characteristics comparable with ordinary incandescent lamps. The project will result in acquisition of knowledge and know-how in Denmark which will enhance the opportunities for realisation of energy savings with LED lighting and which will be beneficial to Danish companies that work with development of LED lighting.

2.2 Laser systems

2.2.1 Improvement of spatial and temporal coherence of a broad area laser diode using an external-cavity design with double grating feedback

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Due to their compactness, low costs and high efficiency, laser diodes are used in a wide range of applications from medical diagnostics and therapies to printing technologies. Since the invention of semiconductor lasers in 1962,[1] their performance has improved steadily, primarily in terms of lifetime and power level. The output power, however, is limited due to catastrophic optical damage of the laser output facet. This limitation may be overcome by increasing the width of the injection stripe, thus manufacturing broad-area lasers (BALs), or by fabricating monolithic laser diode arrays (LDAs) with several injection stripes separated by, e.g., proton implantations. However, these techniques result in uncontrolled emission of several lateral modes with a double-lobe far field pattern[2] and, thus, lasers with poor spatial and temporal coherence. The coherence properties are crucial in many applications, such as efficient coupling to optical fibres or non-linear generation of new frequencies. For example, crystals for second harmonic generation (SHG) or optical parametric oscillators (OPOs) require pump lasers with high spatial and temporal coherence. A remaining problem using diode lasers as pump sources for such applications is maintaining high power while improving their coherence.

In this work,[3] we demonstrate a novel technique for narrow bandwidth and highly improved lateral mode operation of a high-power, broad-area laser diode. The system, see Figure 1, uses simultaneous asymmetric feedback from the first diffracted order and the zeroth reflected order of a diffraction grating.

The grating is arranged in a configuration similar to a Littman configuration, but with additional feedback from the zeroth order. By means of spatial filters the two feedback paths are arranged to operate in a constructive manner leading to simultaneous improvement of the spectral and the spatial properties of the laser diode. The output from the system is extracted from the zeroth order.

The laser system operates in the well-known asymmetric double-lobed far field pattern with the larger lobe being extracted as the output. The bandwidth of the enhanced output beam has been measured to 0.07 nm, which corresponds to an improvement of a factor of 17 compared with the bandwidth of the freely running laser, see Figure 2. The output from the system contains 54% of the energy reaching the grating, or 75% of the power reflected into the zeroth order. The overall efficiency from freely running laser to output of the system is 43%. This number can be improved remarkably by using micro-optics and better coatings.

The improvements in both spatial and temporal coherence opens the possibility of using this laser system in applications such as frequency doubling and pumping of OPOs.

The project is funded by the Danish Research Agency through The Danish Technical Research Council's grant no. 9901433.

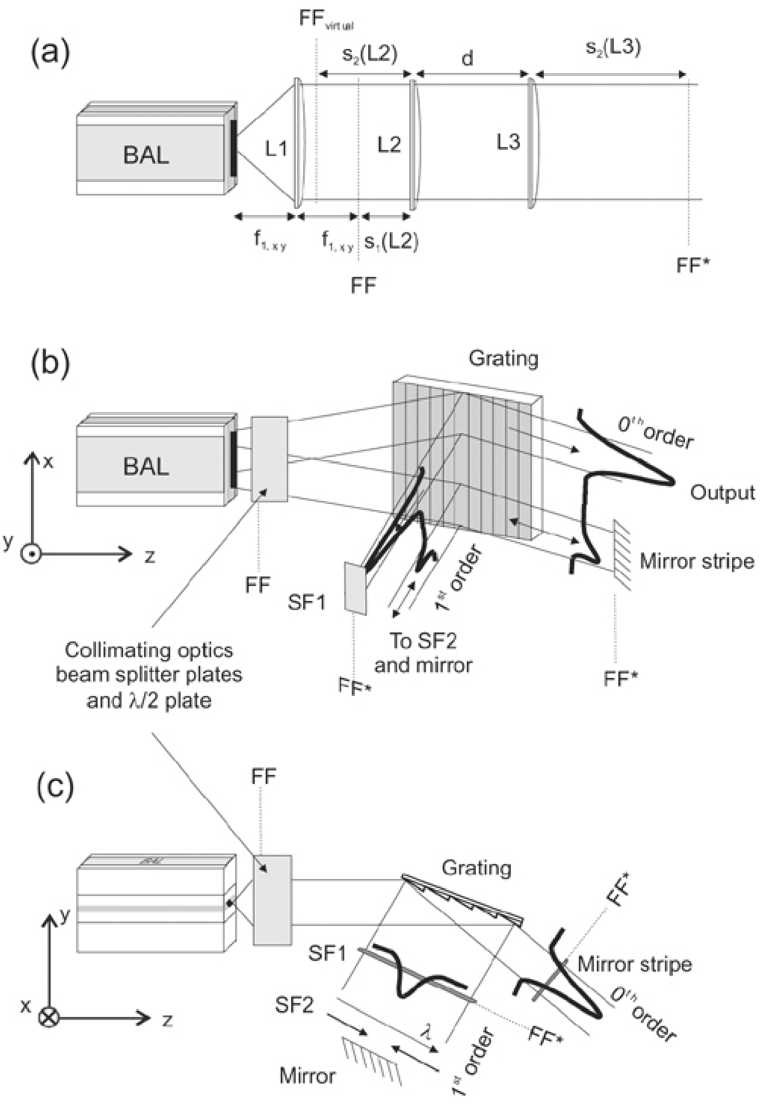

Figure 1. Collimation and generation of image planes (a), side view (b), and top view (c) of experimental set-up. BAL: Broad area laser; Li: Collimating lenses; f1,x: Focal length of L1, s1(Li): Distance from object plane to Li; s2(Li): Distance from Li to image plane; FF: Lateral far field plane; FFvirtual : Virtual image plane of FF; FF*: Image plane of FF; SF1: Spatial filter in the lateral direction; SF2: Spatial filter in the transverse direction; x, y, z: Lateral, transverse and longitudinal directions, respectively. The shapes of the intensity profiles have been outlined in black.

1. R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, Phys. Rev. Lett. **9**, 366-368 (1962).

2. J.-M. Verdiell, H. Rajbenbach, and J. P. Huignard, J. Appl. Phys. 66, 1466-1468 (1989).

3. E. Samsøe, P. E. Andersen, S. Andersson-Engels, and P. M. Petersen, "Improvement of spatial and temporal coherence of a broad area laser diode using an external-cavity design with double grating feedback," Opt. Express **12**, 609-616 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-4-609

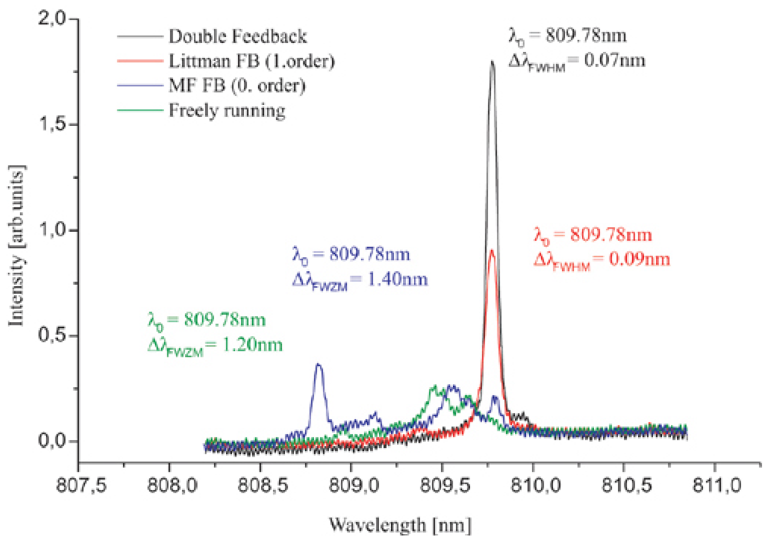

Figure 2. Spectrum of the double and single feedback laser. Black spectrum: Double feedback applied; Red spectrum: Feedback from first order applied; Blue spectrum: Feedback from zeroth order applied; Green spectrum: Freely running laser.

2.2.2 High-brightness laser source based on self-injection locking of a broad-area diode laser with a 1000 µm wide emitter

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High-power, broad-area semiconductor diode lasers (BALs) are an attractive laser source for many applications from the graphics industry to medical diagnostics and therapies due to their compactness, low costs, high efficiency and long lifetime. However, these devices suffer from poor spatial coherence due to the broad emitter aperture. A way of improving the spatial coherence properties and, thereby, the brightness of such lasers is to introduce feedback to the diodes by off-axis self-injection locking.[1]

The project aims at developing high-brightness diode laser system for the printing industry. Since the commercially available single-element BALs with emitter widths less than 500 µm can only produce several watts of optical power, we suggest to apply the self-injection locking to BALs with an extraordinarily broad stripe width in order to obtain several watts of optical power from a BAL and, at the same time, improve the beam quality significantly.

Figure 3 shows what happens to the far-field intensity profile along the slow axis of an antireflection coated diode laser with a 1000 µm wide emitter when the self-injection locking is applied to the laser.[2] The beam width, measured in the far-field plane, is narrowed 40 times, and the peak intensity is enhanced 15 times compared with the freely running laser. An output power of 2.05 W is obtained with a beam quality factor M^2 equal to 2.7 from the self-injection locking laser system.

The project is partly financed by Esko-Graphics.

1. M. Løbel, P.M. Petersen and P.M. Johansen, "Single-mode operation of a laser-diode array with frequency-selective phase-conjugate feedback", *Opt. Lett.* **23**, 825-827 (1998).
2. M. Chi, B. Thestrup and P.M. Petersen, "Self-injection locking of an extraordinarily wide broad-area diode laser with a 1000 m wide emitter", *Opt. Lett.* (accepted).

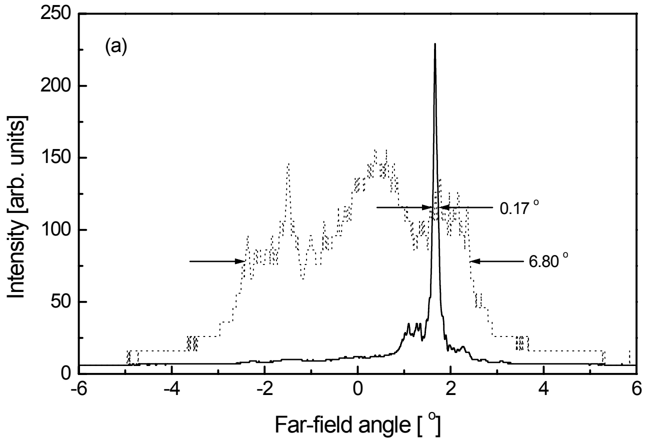

Figure 3. Far-field profiles measured along the slow axis for the freely running laser (dotted curve) and the self-injection locking laser system (solid curve) at the injected current of 7.0 A. For clarity, the data for the freely running laser have been multiplied by 10.

2.3 Laser ablation and pulsed laser deposition

2.3.1 Surface morphology of polyethylene glycol films produced by matrix-assisted pulsed laser evaporation (MAPLE)

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Polymers and biomaterials used as thin films have a wide range of pharmaceutical, technical and bioengineering applications. Thin films of polymers can be used as chemiresistors, drug delivery and chemoselective coatings. We have explored the surface structure of polymer films produced by the matrix assisted pulsed laser evaporation (MAPLE) technique at different substrate temperatures.

PEG (polyethylene glycol) was deposited on Si substrates from a water ice matrix, kept at – 50 °C, while the substrate temperature was varied from room temperature to 70 °C. Frozen solutions of 1% weight PEG were irradiated by 6 ns UV pulses at the wavelength of 355 nm. The deposition gave a deposition rate up to 0.7 ng/cm^2 per shot and complete coverage of substrate surface by films of various degrees of thickness and roughness. The polymer films studied by optical microscopy, see Figure 4, demonstrate a correlation between substrate temperature and film structure. At room temperature, clusters of the size of 5-10 micrometres emerge. At higher temperatures, but still below the polymer melting point (45-50°C), a characteristic cluster structure, with clusters of the size of 20-200 micrometers, is seen.

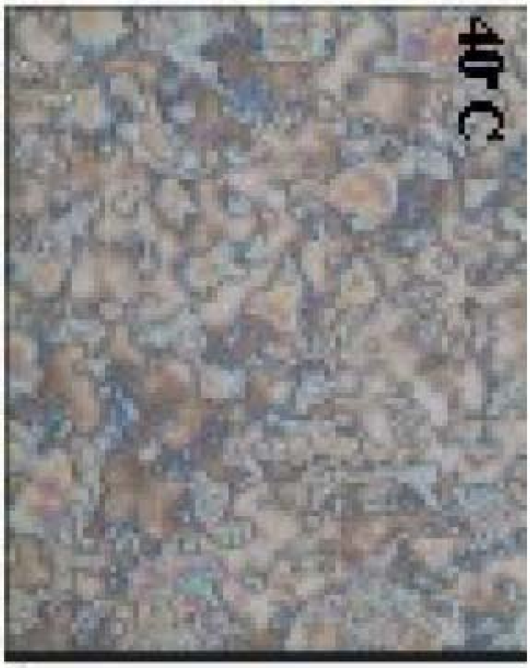

Figure 4. Optical picture of a silicon substrate completely covered by a 20-nm thin (light brown) PEG layer. PEG clusters of the size of 20-40 µm are seen on the top of the thin PEG layer.

2.4 Biomedical optics and optical sensors

2.4.1 Fabrication of microlens arrays for optical mouse using the Nanoplotter

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The goal of this project is to design and fabricate polymer injection-moulded microlens arrays for the emission and recollection of laser light in a newly developed optical sensor system.

The fabrication comprises a series of processing steps starting from direct laser writing of the microlens surface topographies in a 3 µm thick layer of photoresist using the nanoplotter (www.nanoplotter.dk). The photoresist microlens arrays are shown in the micrograph in Figure 5. The three 1 x 1 mm^2 arrays comprise two cylindrical lens arrays and one spherical lens array. The surface topographies obtained in the photoresist are verified by using atomic force microscopy, see Figure 6, where a nearly perfect match to the desired curve shapes can be obtained, see Figure 7.

The second processing step is to transfer the microlens topographies into a nickel shim, shown in Figure 8. This process gives a perfect replica of the original lens shapes, which is constantly verified by comparing atomic force micrographs of the two topographies. The shims are injection moulded in a polymer material called polyetheramid (tradename ULTEM 1010) at an external collaborator, after which the final optical performance of the total element is characterised.

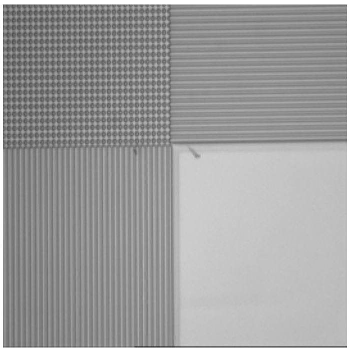

Figure 5. Micrograph of microlens arrays recorded by direct laser writing in photoresist using the Nanoplotter.

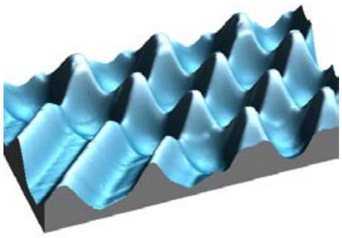

Figure 6. Atomic force micrograph of microlens topographies. The microlens pitches are 15 microns; the sags are 1.5 and 2.8 microns for the cylindrical and the spherical arrays, respectively.

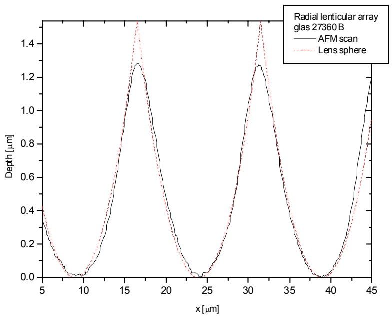

Figure 7. Curve shapes of the desired (red) and realised (black) cylindrical lens profiles.

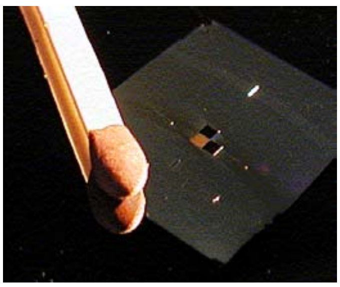

Figure 8. Photograph of microlens arrays transferred to a nickel shim.

2.4.2 Optical waveguide sensor for monitoring living cell morphology

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Optical waveguide sensors have so far been used to detect biological materials at the surface of the sensor in aqueous cover media. These devices are based on the phenomenon that any change in the refractive index of the cover media shifts the effective refractive index of the surface mode. This change is detected through an evanescent optical field decaying exponentially from the surface of the sensor. Until recently, the penetration depth of this evanescent field was limited to ~100 nm. This reduced the sensitivity when we aimed at refractive index changes far from the sensor surface, for example in the case of detection of bacteria or living cells that are 1-10 microns in size.

Recently, a new type of waveguide design with the so-called reverse symmetry has been suggested to overcome the fundamental limitations of the cover penetration depth. In this design, the refractive index of the waveguide substrate is lower than the refractive index of the aqueous cover media, i.e. lower than 1.33; see Figure 9. With this new configuration the penetration depth can be tuned, in principle, up to infinity by simply choosing the right thickness of the waveguiding film. In this way the waveguide can be tailor-made to embed larger biological substances into its evanescent field. This feature makes the reverse symmetry waveguide well suited for the monitoring of cell morphology.[1,2]

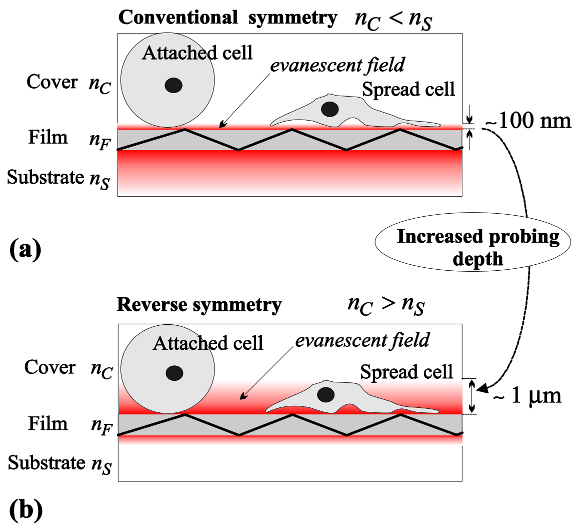

Figure 9. (a) Conventional and (b) reverse symmetry waveguide designs.

1. Horvath R, Pedersen HC, Skivesen N, Selmeczi D and Larsen NB, "Monitoring of living cell attachment and spreading using reverse symmetry waveguide sensing" *Applied Physics Letters* **86**, 071101 (2005) (Cover Image).
2. R. Horvath, N. Skivesen, N.B. Larsen, H.C. Pedersen "Reverse symmetry waveguide for optical biosensing" in "Frontiers in Optical Sensing: Novel Principles and Techniques" (Springer) (Invited Book Chapter).

2.4.3 Metal-clad waveguides for biosensing

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Optical planar waveguide sensors are based on evanescent sensing and measures refractive index changes in the media surrounding the waveguide. The electromagnetic field propagating in the waveguide extends into the surrounding media as an evanescent electromagnetic field whereby the refractive index of the surrounding media contributes to the effective refractive index detected by the waveguide. One interesting field of application of waveguide sensors is rapid, online detection of micron-size particles such as bacteria and whole cells. For this purpose one important feature for improving the sensitivity is to increase the penetration depth of the evanescent field in the cover. Conventional optical waveguides have a limited penetration depth of the evanescent field in the cover solution of approximately 200 nm whereas the metal-clad waveguide (MCWG) sensor can be operated with an unlimited penetration depth when the film thickness is equal to the cut-off thickness.[1]

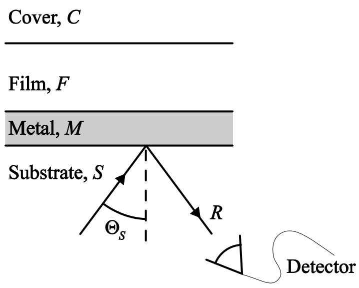

Figure 10. Metal-clad waveguide sensor configuration.

A typical optical waveguide sensor is based upon monitoring the resonance angle at which light is coupled into the waveguide. Hence, the in-coupled light intensity versus the illumination angle gives rise to a peak-type sensorgram. As opposed to this, the MCWG is used in reflection mode, see Figure 10, just as the well-known surface-plasmon resonance (SPR) biosensor. As a result, in this case the sensorgram typically consists of a dip in reflectance versus illumination angle, giving rise to a dip-type sensorgram, see Figure 11.

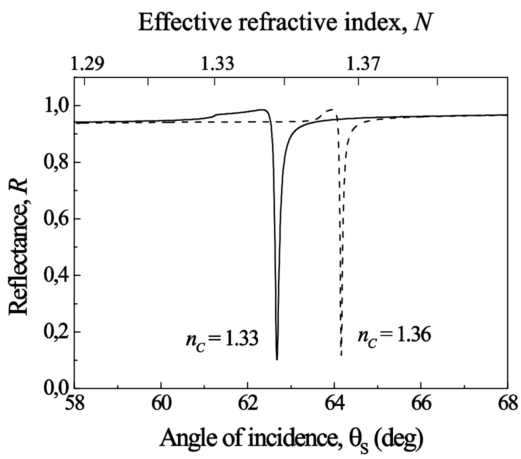

Figure 11. Dip-type sensorgrams of a conventional metal-clad waveguide configuration: glass, 50 nm gold, 300 nm SiO_2 and samples $n_C = 1.33$ & $n_C = 1.36$.

The MCWG sensor can be used in two different operation modes depending on the metal used for the cladding. The typical dip-type operation (Figure 11) is suitable for waveguide configurations with a thin layer of low-loss metal (small imaginary part of the permittivity), while the peak-type operation (Figure 12) is possible using an ultra thin layer of high-loss metal (large imaginary part of the permittivity).[3] For the peak-type MCWG the peak angle in the sensorgram is exactly identical to the critical angle at the film-sample interface, see Figure 12. This causes the probing depth of the evanescent field to increase to infinity. Moreover, the sensitivity increases to unity, which is also approximately five times larger than for ordinary waveguide sensors.[1] The dip-type MCWG can be operated close to cut-off film thickness, but will have a limited penetration depth of the evanescent field to approximately 1 μm. Thus the penetration depth is still higher compared with the conventional waveguide sensors.[2] The peak-type MCWG can for one configuration only be operated with one polarisation (either TE or TM) while the dip-type MCWG can support both a TE and a TM mode. MCWG sensors consequently facilitate two different operation modes, dip-type and peak-type operation, which are optimal for different sensing purposes such as refractive index measurements, detection of micron-scale objects or measuring thin ad layers on the sensor surface.

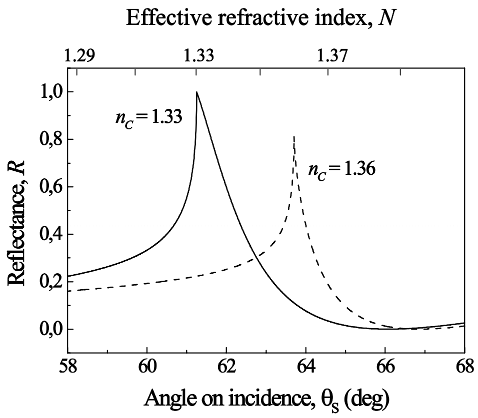

Figure 12. Peak-type metal-clad sensorgrams for a 5 nm titanium-clad waveguide, ε = -3.9 + i12.2: Glass, 5 nm Ti, 250 nm SiO_2 and samples n_C = 1.33 & n_C = 1.36.

1. R. Horvath, L.R. Lindvold and N.B. Larsen, "Reverse-symmetry waveguides: theory and fabrication,"Applied Physics B **74**, 383 - 393 (2002).
2. N. Skivesen, R. Horvath and H.C. Pedersen, "Optimization of metal-clad waveguide sensors", accepted for publication in Sensors & Actuators B.
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2.4.4 Micro-interferometric backscatter detection for label-free sensing of biochemical interactions

H.S. Sørensen, J.C. Latham, D. Markov*, D.J. Bornhop* (*Chemistry Dept., Vanderbilt University, Nashville, TN, USA), N.B. Larsen (Danish Polymer Centre, Risø National Laboratory, Denmark) and P.E. Andersen*
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Micro-interferometric backscatter detection (MIBD) is a highly sensitive method for measuring the refractive index in ultrasmall sample volumes.[1] This technique may be utilised for both absolute[2] ($\Delta n = 10^{-4}$) and relative[3] ($\Delta n = 10^{-8}$) measurements. MIBD has a very simple set-up comprising of a laser that impinges on a liquid-filled micro-flow channel, whereby a highly modulated interference pattern occurs. When the refractive index of the liquid changes, the light and the dark spots in the fringe pattern shift position. This position change is then monitored for refractive index detection.

We have used MIBD for detection of bio-chemicals interacting inside the micro-flow channel. The analytes of interest have been DNA-strings and protein receptor interactions. With DNA-strings we have detected different binding energies when having a three base pair mismatch compared with complementary DNA. The data have been verified by comparing binding enthalpies obtained from isothermal titration calorimetry, although in a much smaller sample volume. Real time binding curves have been obtained for Protein A reacting with Human IgG (growth hormone). This has enabled us to retrieve binding values (k_D) for this system label-free in a very simple sensing set-up, where the micro-flow channel has been a rectangular PDMS (silicone) flow chip. The chip has been manufactured in a standard one-step SU8 photolithography process. Our preliminary modelling of these PDMS-glass slide flow chips has shown that by changing to a circular channel geometry two orders of magnitude in sensitivity is to be gained.

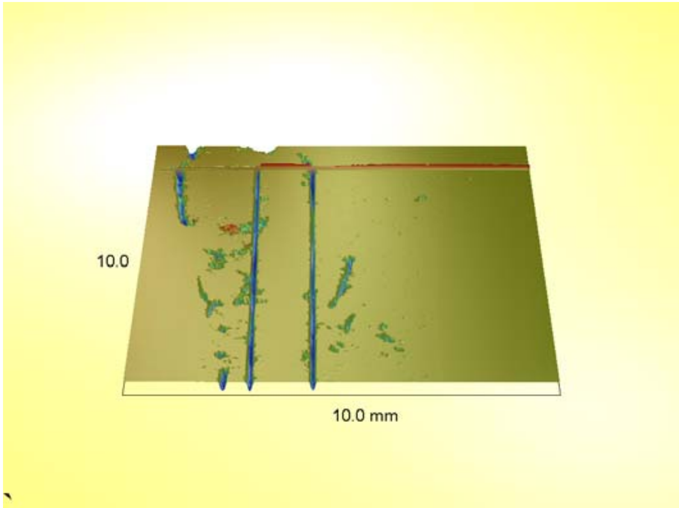

Figure 13. 3D image, obtained by Dektak profilometer, showing two parrallel isotropically etched channels in silicon.

Great efforts have been used to manufacture these circular structures. In the same process our goal is to end up with a flow chip completely in polymer material. The microstructure fabrication is a multiple-step clean-room process that includes E-beam evaporation and HF-based etching in silicon, see Figure 13. The microstructure has been electroplated into nickel shims. Via microinjection moulding we have fabricated numerous open-channel flow chips in Topas 8007 and 5013 with semicircular geometry. These polymer chips have been sealed to form our final micro-flow devices, now ready to MIBD experiments, Figure 14.

1. D. J. Bornhop, *Appl. Opt*. 1995, **34,** 3234-3239.
2. H. S. Sørensen, H. Pranov, N. B. Larsen, D. J. Bornhop and P. E. Andersen, *Anal. Chem*. 2003, **75**, 1946-1953.
3. D. Markov, D. Begari and D. J. Bornhop, *Anal. Chem*. 2002, **74**, 5438-5441.

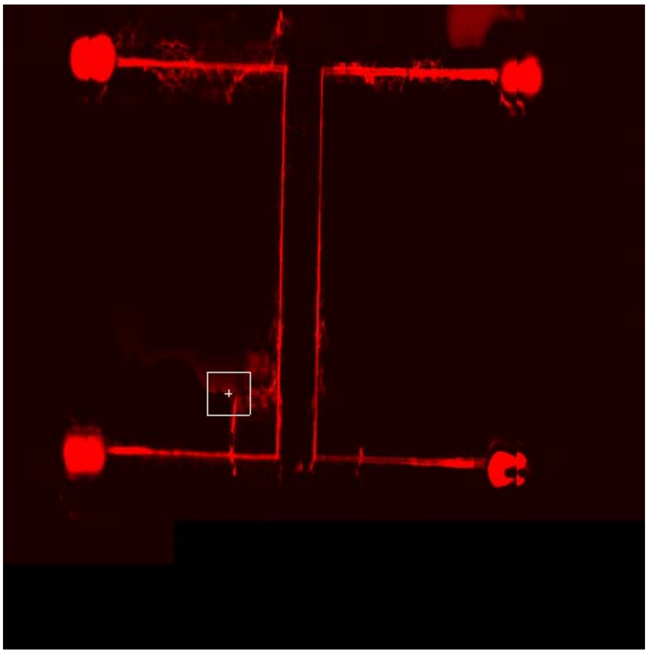

Figure 14. Microscope image of a sealed polymer chip with Rhodamine dye as the red liquid inside the flow channel. Two pieces of Topas 8007 are thermally bonded so that no liquid is exchanged between the channels.

2.5 Nanotechnology

2.5.1 Photodimerisation in dipeptides for high-capacity optical storage

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Ultrahigh capacity archival storage is an important 21st century requirement for the information technology society. Currently, a storage capacity of approximately 25 Gbytes at 405 nm has been achieved in a 5.25” disc in the Blu-Ray system. One way of increasing the storage capacity is to employ even shorter wavelengths. Taking the 25 Gbytes on a 5.25” disc, with a 405 nm laser source and 0.85 NA optics as specified for the recent Blu-Ray system as our starting point, the storage capacity can be increased to approximately 60 Gbytes by using a 250 nm semiconductor laser. Such lasers are presently under development in a number of laboratories around the world. We suggest the possibility of using a photodimerising medium as the material for information storage. We propose to employ photodimerising bases in DNA and RNA such as thymine and uracil attached to a short peptide chain. The peptide chain possesses the necessary length and rigidity to ensure a proper orientation of the chromophores to facilitate cycloaddition without large physical movements. The photodimerisation process is envisaged to give a sufficient change in the absorbance of thin films of peptides to allow a grey scale of 2-3 bits increasing the storage capacity of 120-180 Gbytes per side. Optical nonlinearity may enable us to use the same laser for writing and reading. Furthermore, a change in the volume of the material during the dimerisation process in the material may enable us to fabricate high-capacity removable CD-ROMs through the process of replication.

1. P. S.Ramanujam and R. H. Berg, Appl. Phys. Lett. 85, 1665 (2004).

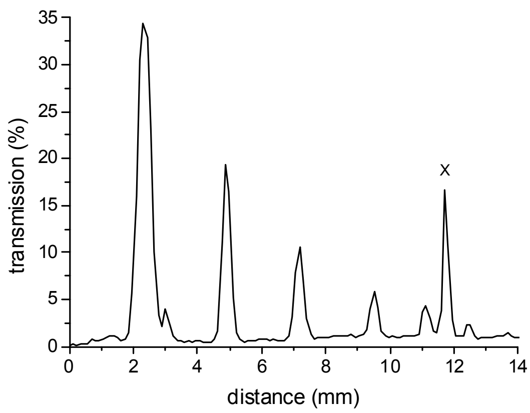

Figure 15. An example of 5-bit storage. The peak marked with a cross is due to a defect in the film.

2.6 Light emitting diodes

2.6.1 Energy savings with light emitting diodes

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Light emitting diode (LED) lighting has developed tremendously in recent years and is regarded as the light source of the future. Currently the efficiency of LEDs is doubled every second year. Within the near future LEDs are expected to become more energy efficient than the most efficient conventional lighting. The best performing coloured LEDs today have an efficiency of 60 Lumen/Watt while incandescent lamps produce 10-15 Lumen/W. The most efficient light sources today produce 125 Lumen/W.

In addition to the energy savings, LEDs have a number of other advantages: very long lifetime - up to 100.000 hours (save costs for replacement of light sources), large robustness as regards bumps and shaking, very small heat production and no IR or UV rays.

The objectives of the present project are:

- to develop a prototype of a 3 W white LED light source that can replace ordinary 15-20 W incandescent or halogen lamps with conventional sockets
- to develop optics for LEDs that can both mix coloured light to white light and spread the light in order to obtain light characteristics comparable with ordinary incandescent lamps
- to map the opportunities and produce a catalogue with ideas for use of LEDs with the technology of today
- to develop lighting fixtures and produce ideas for fixtures for a range of purposes based on the white LED light source in the project and other relevant LEDs on the market.

The project will result in acquisition of knowledge and know-how in Denmark which will enhance the opportunities for realisation of energy savings with LED lighting and be beneficial to Danish companies that work with development of LED lighting.

For the optimal design of a LED-based white light source, a test laboratory for characterisation of individual LEDs and general light sources will be established. Measurements of spatial radiation patterns, radians, luminance and spectral distribution are performed. The correlated colour temperature and specific and general colour rendering indices for a white light source are calculated according to CIE standards.

These competencies are used to design LED white light sources based on the RGB technology with desired colour temperature, and to optimise the luminous power and colour rendering properties of the light source.

Numerical ray tracing of LED light is a powerful tool in connection with optimizing LED light source designs. In the present project, we have developed 3D computer models of single LEDs, as well as a model of a white LED bulb based on the RGB technology. With these models it is possible to investigate numerically the irradiation patterns from the LED light sources as well as the colour mixing of the LED bulb design before actually constructing the physical bulb.

The computer models follow light rays from the LED chips through various optical elements such as the LED cone, lenses, etc, while taking into account the refraction, the reflection and the absorption in the various elements. The irradiance patterns on selected 2D detector planes can then be calculated.

Figure 16 shows an example of simulated irradiance patterns for five different colours in a specific white LED bulb presentation at a detector position of 10 cm from the bulb. The five colours are chosen so their colour spectra can be combined to a white light spectrum. These irradiance patterns are then converted into a set of RGB coordinates using measured LED spectra for the various coloured LEDs used in the model. Figure 17 shows the corresponding RGB presentation of the total simulated irradiance pattern from the bulb model. As expected, significant colour mixing is observed.

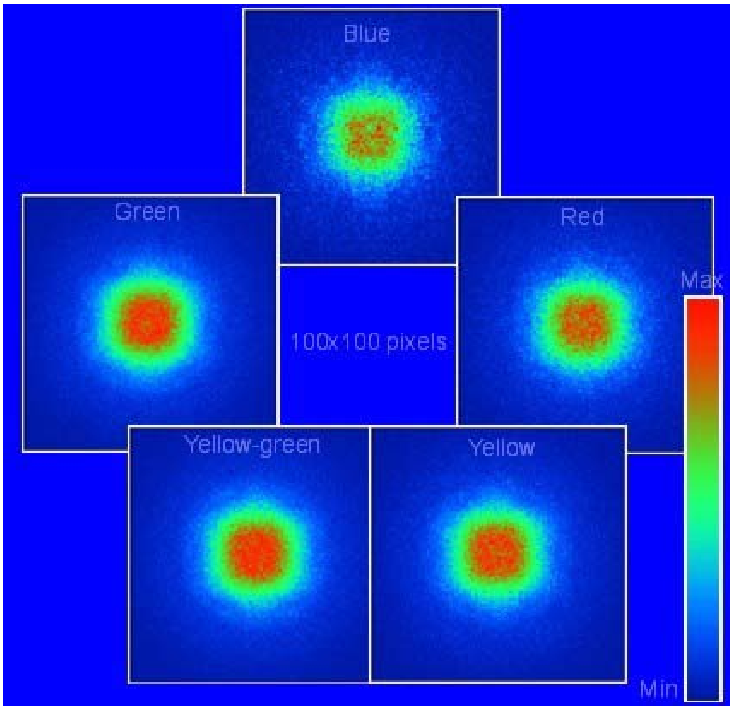

Figure 16. Simulated irradiance patterns from various colours in a LED bulb model at a detector position 10 cm from the model back plane. The detector dimensions are 40 cm x 40 cm. The intensities for the various colours have been normalised and cannot be mutually compared.

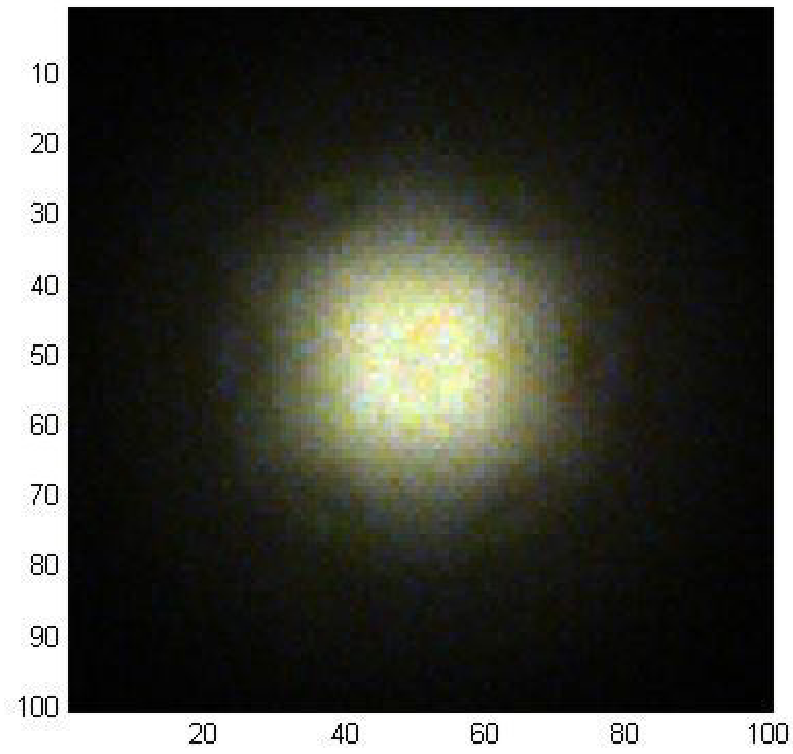

Figure 17. RGB presentation of the total irradiance pattern from a LED bulb model calculated at the detector plane position 10 cm from the model back plane. The detector dimensions are 40 cm x 40 cm and the number of pixels is 100 x 100.

2.7 International collaboration

2.7.1 BRIGHT.EU – Wide wavelength light for public welfare: high-brightness laser diode systems for health, telecom and environment use

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BRIGHT is an integrated project under the sixth European Frame programme starting 1 July 2004.

High-brightness laser diode technology is a key enabling technology for the information society of tomorrow, especially in the fields of health care, telecommunication, environment and security.

The development and achievements of the information society rely on a smart use of the information for applications such as imagery or telecommunications. The electron and the photon are the two main information carriers, the latter having taken an increased role since the end of the 1970s, when engineers demonstrated the efficiency of optical fibre transmission.

Since then, the demand for high-brightness sources has increased continuously. Laser diodes already offer extraordinary compactness at a reasonable cost and now play a central role in telecommunication. However, their brightness still needs to be improved to spread their large-scale uptake across the information society; the main challenge is to couple more light power in smaller diameter fibres.

The WWW.BRIGHT.EU consortium proposes a long-term vision aimed at pushing the limits of the current laser diode technology towards higher brightness, and at demonstrating applications such as:

- Medical imagery for cancer therapy
- Amplifiers for telecommunication networks

The approach consists of mobilising the expertise of the main European actors of the laser diode core technology, and coupling it with highly innovative optical technologies such as, e.g., smart cavity concepts for higher efficiency and tuneability. Industrialisation constraints will be widely addressed through packaging and reliability studies.

One way to achieve higher brightness of a single broad diode laser is to introduce mirror feedback to the diode along the critical axis (the stripe) using an off-axis self-injection locking technique.[1] However, this technique cannot directly be applied to high-power 5-20 W broad diode laser bars as they, typically, consist of several mutually incoherent laser segments. Within this project, we will develop new external cavity schemes that combine wavelength-multiplexing techniques[2] with off-axis self-injection locking techniques. The purpose is to obtain an overall improvement of the laser beam quality that can exceed the beam quality of the individual laser segments. Figure 18 shows an example of a wavelength multiplexing setup realised at Risø with an 808 nm wide-stripe diode laser consisting of five segments. With this setup, the overall beam quality along the critical axis has been improved with a factor of 4.3 at a drive current slightly above threshold.

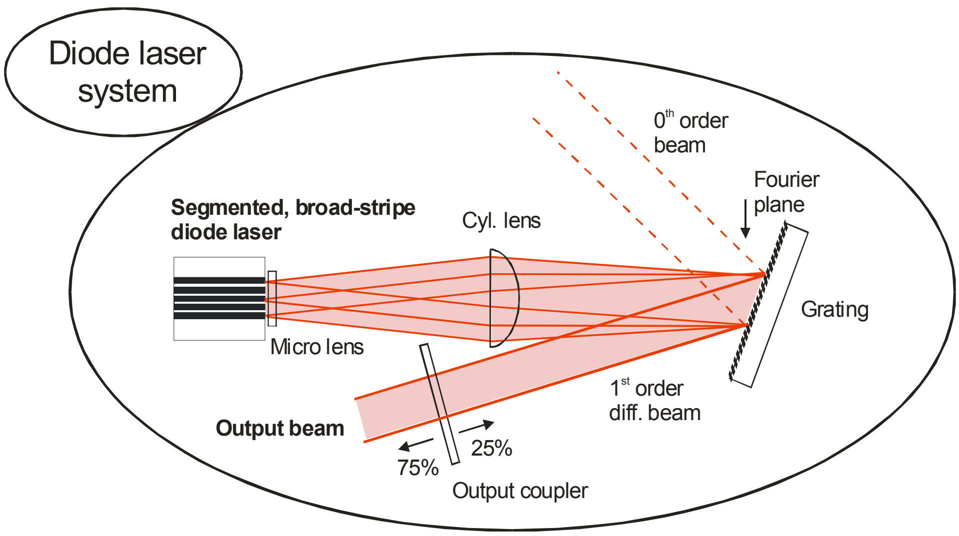

Figure 18. Schematic representation of a wavelength multiplexing set-up that overlaps the output beams from the individual segments in the diode laser bar.

1. B. Thestrup, M. Chi, B. Sass, P.M. Petersen, Appl. Phys. Lett. 82 (2003) 680-682.
2. V. Daneu, A. Sanchez, T.Y. Fan, H.K. Choi, G.W. Turner, C.C. Cook, Opt. Lett. 25 (2000) 405-407.

2.7.2 VELI – Virtual European Laser Institute

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In 2001, a multidisciplinary virtual European laser institute (VELI) was formed with support from the European Commision in order to enhance and promote the available laser expertise in Europe. The BIOP Center (www.biop.dk) was invited to join VELI in order to strongly promote the use of lasers and optical methods in the field of biophotonics.

The motivation for establishing VELI is to create one main portal through which access to experts in the fields of laser physics, technology and applications is enabled. Industry in general, but in particular small and medium sized enterprises may experience significant difficulties reaching the enormous body of knowledge that exists at the various laser institutes across Europe. Moreover, from the point of view of industry, it is difficult to gain insight into the existing and available expertise in lasers and optical measurement technologies at the various dispersed laser centres. Therefore, the multidisciplinary VELI was formed. The purposes of VELI are:

- to increase the transparency and knowledge of available laser expertise in Europe,
- to remove the current inefficiency (or lack) of exploitation of new laser knowledge and techniques,
- to create common agreements and procedures for knowledge transfer.

This European effort will achieve the critical mass in human and technological terms bringing together the expertise and resources needed and will thus enhance the competitiveness of European industry.

In the VELI network, the BIOP Center collaborates with 15 leading research institutions specializing in laser physics and applications of lasers. The wide variety of competencies of the participating scientists representing different disciplines supports the creation of an outstanding state-of-the-art knowledge base on a European level, including advanced applications of lasers in bio-photonics.

The major output of the VELI project is:

- A fully operational core network consisting of 15 leading professional laser institutes in Europe possessing core competencies in the fields of laser technology.
- A database containing state-of-the-art expertise, experience and knowledge formerly dispersed at various laser institutes. Moreover, the database contains the gathered knowledge generated from the extensive list of industrial needs at small and medium sized enterprises.
- A virtual surrounding i.e. a site where the requests coming from the small and medium sized enterprises (industrial needs/demand), meets the available expertise and the wide array of possible applications of laser and laser technology (laser institute supply) speeding up the realisation of potentially new and highly competitive applications.

In accordance with the aims (see the first bullet in the list above), an important milestone was achieved during 2003 when the European Laser Institute (ELI) was founded. This new association is now operational and open to new members. The organization is responsible for the online laser portal and its contents can be found at www.eli-online.org. The project itself ended June 2004.

3. Optical diagnostics and information processing

3.1 Introduction

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During the year 2004 a new strategy for 2006-09 was formulated for Risø National Laboratory, a strategy that emphasises the visibility and impact of our scientific work in society. These strategic goals should be pursued through innovation and through technical collaboration with industry. The research programme has successfully contributed to these goals. For one existing spin-off company, our persistent technical effort has led to both economic payoff as well as to new market opportunities. The coming year may prove the full success of this work. In 2004 the scientific programme has established commercial research and development contracts with several companies in the global community. These contracts are based on the strong patent portfolio of the programme. In order to support applied research and development further, the programme has in 2004 successfully established a network of excellence, funded by the Ministry of Science, Technology and Innovation, within the field of biophotonics.

The visibility is also promoted through our contribution to the Danish educational system. One such activity is within the field of bio-medical optics (Graduate School on Biomedical Optics and New Laser Systems). Another such activity is a course on statistical optics at the University of Southern Denmark. Finally, a number of dissertations have been submitted from the research programme, thereby transferring our key competencies to a new generation of students within the optics field, an activity that has proved to benefit both parties.

Scientifically the year 2004 was extraordinarily good, i.e. 22 peer-reviewed articles were published in a series of scientific letters and journals. Thus, the programme proved its ability to be at the forefront in the international optics community.

Furthermore Jesper Glückstad received his degree as Doctor Technices for his dissertation on “The Generalised Phase Contrast Method.” This work has resulted in a novel optical micromanipulation system, awarded by the Danish magazine “Ingeniøren” as one of the Danish top five most innovative inventions in 2004.

In the international arena we will particularly mention the two contribution to the prestigious special edition of “Optics and Photonics News”, namely “Optics in 2004”. One contribution is “Optical Manipulation of High- and Low Index Particles and Living Cells”, the other is “Characterizing Tissue Optical Properties by Use of Optical Coherence Tomography for Diagnostics.” Both articles present research that will be pursued in the coming year.

IR techniques are becoming more and more important within the field of combustion as well as within biological research. Here, Risø holds a strong position as being the national reference site for non-contact temperature measurements. The work is carried out in close collaboration with Danish industry, universities and technological institutes, thus underlining its positive impact and importance to the Danish society. We foresee a growing demand in this field in the years to come.

3.2 Biophotonics

3.2.1 Dual-beam FT-NIR spectrometry

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In an earlier published work it was demonstrated that a dual-beam FT-NIR set-up could be used for quantitative determination of urea (0-40 mg/dL) and glucose (0-250 mg/dL) in aqueous solutions and medical samples.[1,2] Expected advantages of the dual-beam set-up as compared with single-beam operation are: (1) reduced analog-to-digital converter (ADC) noise (or quantisation noise) contribution to the spectra due to the fact that the available bits at the ADC can be used to represent the reduced ac-amplitude of the dual-beam interferogram, (2) fluctuating noise sources are minimised by the simultaneous measurement of sample and reference beam. The advantages with dual-beam were obtained with spectral data and chemometrics.

In order to trace the differences between single- and dual-beam operation, a quantitative study of the noise sources based on measured interferograms was initiated. The experimental set-up has been improved compared with that described in earlier published work.[3] The positions of the input mirrors are made adjustable in order to be able to fine-tune the alignment and thereby obtain a relatively large nulling ratio that can be reproduced more easily. In addition, glass blasted CaF_2 windows have been placed in front of the halogen light source in order to obtain a diffuse radiation pattern from the source. A diffuse pattern has proved to facilitate the adjustment of the amplitudes of the interferograms by the pinholes in front of the light source. The observed reduction in RMS noise for the dual-beam operation is mainly due to some degree of real-time referencing. It was shown that source scintillations and changes in the concentrations of absorbing atmospheric constituents in the laboratory were partly compensated for during a rather long time of measurement, see Figure 19. This indicates that the number of scans could be increased in order to improve the signal-to noise ratio as compared with single-beam operation. In addition, it is expected that calibrations based on dual-beam data should be more stable over time. This is in agreement with what was observed in our earlier work.

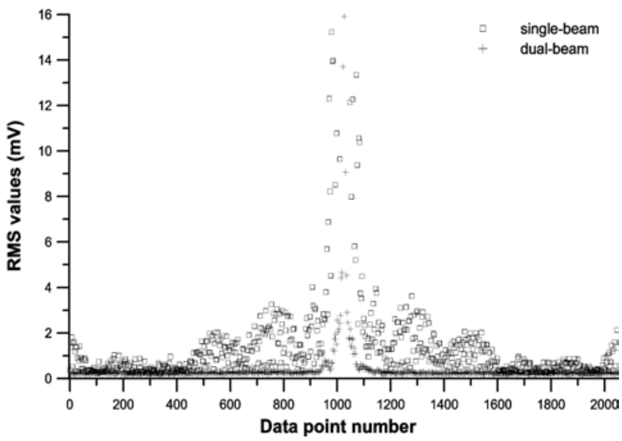

Figure 19. RMS values calculated at each separate retardation point in the interferogram on the basis of a long-term stability test. 35 interferograms were measured during an18 hours time period. The spectral resolution was set at 32 cm^{-1}.

1. P. S. Jensen and J. Bak, “Measurements of urea and glucose in aqueous solutions with dual-beam near-infrared Fourier transform spectroscopy” Appl. Spec. 56, 1593 (2002).
2. Jensen P. S., Bak J., Ladefoged S., Andersson-Engels S. and Friis-Hansen L., “Online monitoring of urea concentration in dialysate with dual-beam Fourier-transform near-infrared spectroscopy” J. Biomedical Optics 9 (3): 553-557, May-Jun 2004.
3. H. Villemoes Andersen, A. Friderichsen, S. Clausen and J. Bak, “Comparison of noise sources in dual- and single-beam FT-NIR spectrometry”, submitted to Appl. Optics January 2005.

3.2.2 Infrared spectroscopic investigations of biofilm on medical devices

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A biofilm is a community of microbes and their extracellular polymers such as proteins and polysaccharides. The formation of biofilm is expected to take place at surfaces in contact with the environment. Biofilm formation in fresh water supply systems, tubes, medical equipment and implants poses a threat to the public health.[1]

This project focuses on the development of an infrared spectroscopic method for diagnosing biofilm on catheters used in hemidialysis. One major problem with long-term catheters is that the patients suffer from infections caused by bacteria colonising the catheters. Current strategies for curing the patient are to remove the catheter and replace it with a new. The scientific goals for this project are (1) to develop a rapid (< ½ hour) and sensitive (small sampling area) infrared spectroscopic method for diagnosing biofilm on implants and (2) to determine whether the biofilm formation takes place on the inside or the outside surface of the catheter. The answer to this question is important for future methods to cure the catheter in-vivo.

The experimental method is based on dried biofilm samplesthat are in contact with an ATR cell (attenuated total reflection). The samples are taken from the removed catheters. The composition of the biofilm is approximately 90% water (removed by drying), polysaccharides and proteins partly produced by the bacteria and, finally, the bacteria. If a biofilm is formed at the catheter the infrared spectrum shows a significant spectral band from polysaccharides. In addition, if the bacteria are present in a detectable amount, spectral features from RNA/DNA are present too, see Figure 20.[2]

1. Michael Wilson, ”Bacterial biofilms and human disease”, Science Progress (2001), 84 (3), 235-254.
2. Jimmy Bak, Tanja Begovic and Søren D. Ladefoged “Measurements of biofilm on central venous catheters for hemodialysis with FT-IR ATR”, Poster to be presented at the Pittcon 2005 conference, Orlando (Fl) February 2005.

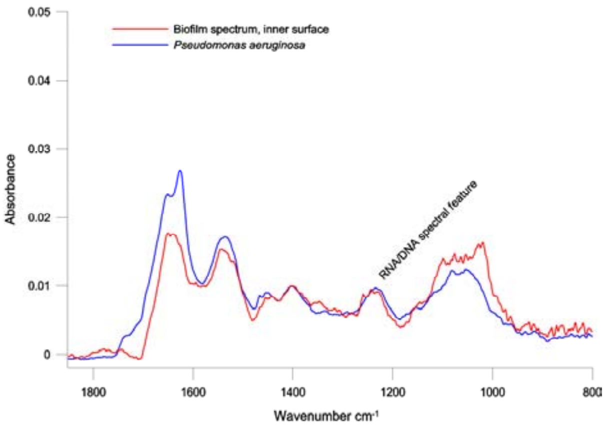

Figure 20. Biofilm spectrum with RNA/DNA spectral features compared with the spectrum from a colony of *Pseudomonas Aeruginosa*.

3.2.3 Surface enhanced infrared absorption spectroscopy

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Surface enhanced infrared absorption spectroscopy (SEIRA) is a relatively new technique. The goal is to improve the detection limits of specific chemical compounds in quantitative analysis. The differences between conventional quantitative spectroscopy and SEIRA should be found in the way the analytical samples are prepared. With SEIRA, the sample under investigation is cast as a thin film over a nanometer thick metal-coated surface; rare metals like gold, platin and silver are the preferred coatings. The mechanism for enhancement of the infrared signal is still debated. It is recognised that the observed enhancements are a combined effect of both chemical and electromagnetic mechanisms.[1]

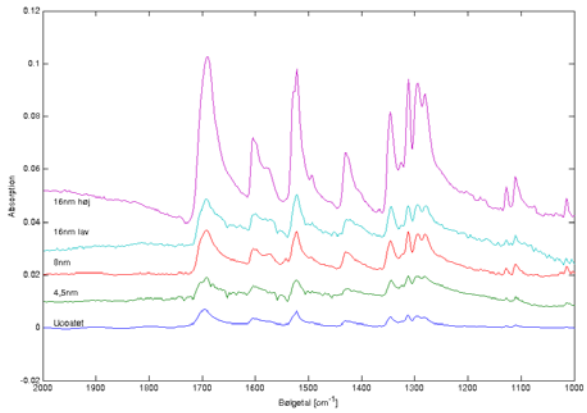

Figure 21. p-NBA signal enhancement observed at the different gold coatings.

In this preliminary work four CaF_2 windows - three coated with gold (4.4, 8 and 16 nm) and one uncoated - were cast with a thin film of para-Nitrobenzoate (p-NBA). p-NBA is one key compound for the demonstration of the SEIRA effect. One major problem with SEIRA, and the Raman based SERS method as well, is the lack of reproducibility. This problem is caused both by the structure of the coating and the method for casting the film on the coating. A tool for casting the film on the infrared transparent windows has been developed. In Figure 21 the preliminary results with p-NBA on the different coatings can be seen. It is observed that enhancement of a factor of 9 can be reached with the thick coating as compared with the compound cast at the uncoated window.[2]

1. Masatoshi Osawa, "Surface enhanced infrared absorption, Near-filed optics and surface plasmons polaritons", Topics Appl.-Phys. 81, 163-187 (2001).
2. Siemen Baader, Louise Brinck and Jesper Heebøll-Christensen, "SEIRA spektroskopi", RUC report, January 2005 (in Danish).

3.2.4 A novel spectroscopic approach for studying the micro- to millisecond dynamics of macromolecules

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We are working on the development of a novel spectroscopic method that will help to access the dynamic properties of macromolecules on the micro- to millisecond timescale. The approach will be applied to study the molecular dynamics of an important pharmaceutical protein drug – human Growth Hormone (hGH). Results of this study will contribute to the understanding of the role of μs-ms motions for the thermodynamic and chemical stability of hGH and for the protein folding in general. Moreover, other areas of protein science where dynamics plays an important role (e.g. in protein function) will benefit from this technique as well.

The proposed approach will present an opportunity to investigate the range of molecular motions not easily accessible by other biophysical techniques. The successful development of this method will expand the accessible range of macromolecular dynamics and will complement the results obtained by NMR spectroscopy.

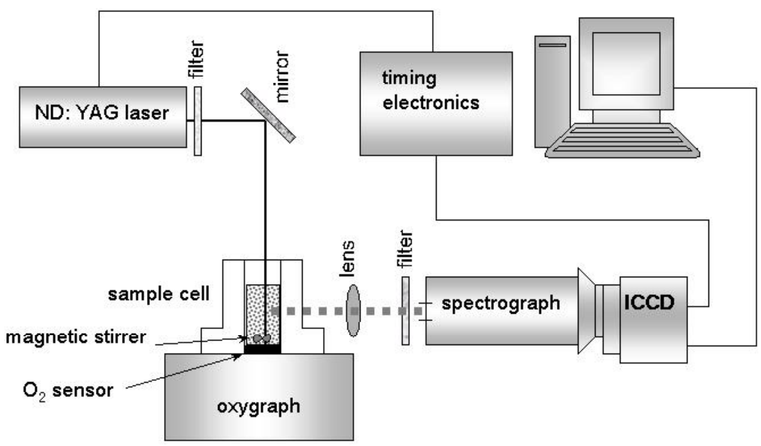

Figure 22. A schematic representation of a time-gated luminescence set-up, showing how the excitation light from the laser is directed towards the sample compartment and then collected by the intensified, gated CCD camera.

The proposed set-up is being constructed by utilising the latest advances in optics technology. After the fulfilment of experimental work, procedures for deconvolution and interpretation of the phosphorescence lifetime properties of the proteins will be developed as well.

The preliminary set-up, capable of measuring the luminescent properties of macromolecules has been built (see Figure 22). It has been tested on the known fluorescent compounds. Currently, we are working on the construction of an appropriate sample chamber that would allow complete removal of oxygen, because even the low amounts of oxygen in the sample act as a strong phosphorescence quencher, leading to the absence of the phosphorescence signal.

3.2.5 Characterising tissue optical properties using optical coherence tomography for diagnostics

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Optical coherence tomography (OCT) is an interferometric measurement technique used for non-invasive imaging of tissue. While the high resolution of OCT allows for visualisation of tissue microstructures previously unresolved, objective interpretation of OCT images at a level where histopathological diagnosis is possible remains a challenge.

In order to address this issue, an alternative approach seems viable. The biological condition of the tissue affects its optical properties. The optical scattering properties, i.e. the scattering coefficient μ_s and the anisotropy factor g, in combination with sample arm optics, determine the depth-dependent amplitude of the OCT envelope. Since the system parameters are known *a priori*, it is possible to extract depth-resolved optical scattering properties from the depth-dependent envelope signal thereby relating tissue optical properties to the tissue condition.

Proper theoretical modelling is imperative since it must adequately describe light-tissue interaction in both single and multiple scattering regimes and sample arm geometries under realistic focusing conditions. Earlier we established a theoretical model[1] meeting these requirements including multi-layered tissues. Recently, we have devised a novel algorithm[2] that fits the averaged depth-dependent envelope signal from a region of interest (ROI) in an OCT image to this model. An example of an OCT image subdivided into ROIs used for curve fitting is shown in Figure 23(A). The new algorithm was successfully tested experimentally for single-layer geometry[2] and numerically for two-layer geometry.[3]

Using this new algorithm[2] we analysed OCT images obtained from postmortem aortic specimen (normal vessels and the three major types of atherosclerotic plaques) searching for variations in μ_s and g in the intimal layer. Figure 23(B-C) displays the distribution of scattering properties (μ_s and g) for the four types of vessels examined. Our results suggest that normal vessels exhibited more uniform scattering properties (15 mm^{-1} < μ_s < 40 mm^{-1} and g > 0.95) than the three types of atherosclerotic lesions, whose scattering coefficient and anisotropy factor were generally lower. To our knowledge, these results represent the first detailed analysis of optical scattering data from the human aortic intima in health and atherosclerotic disease at 1300 nm. Our new approach adds to the qualitative high-resolution imaging offered by OCT with quantitative functional tissue information, which holds promise for the *in vivo* diagnostic value of OCT.

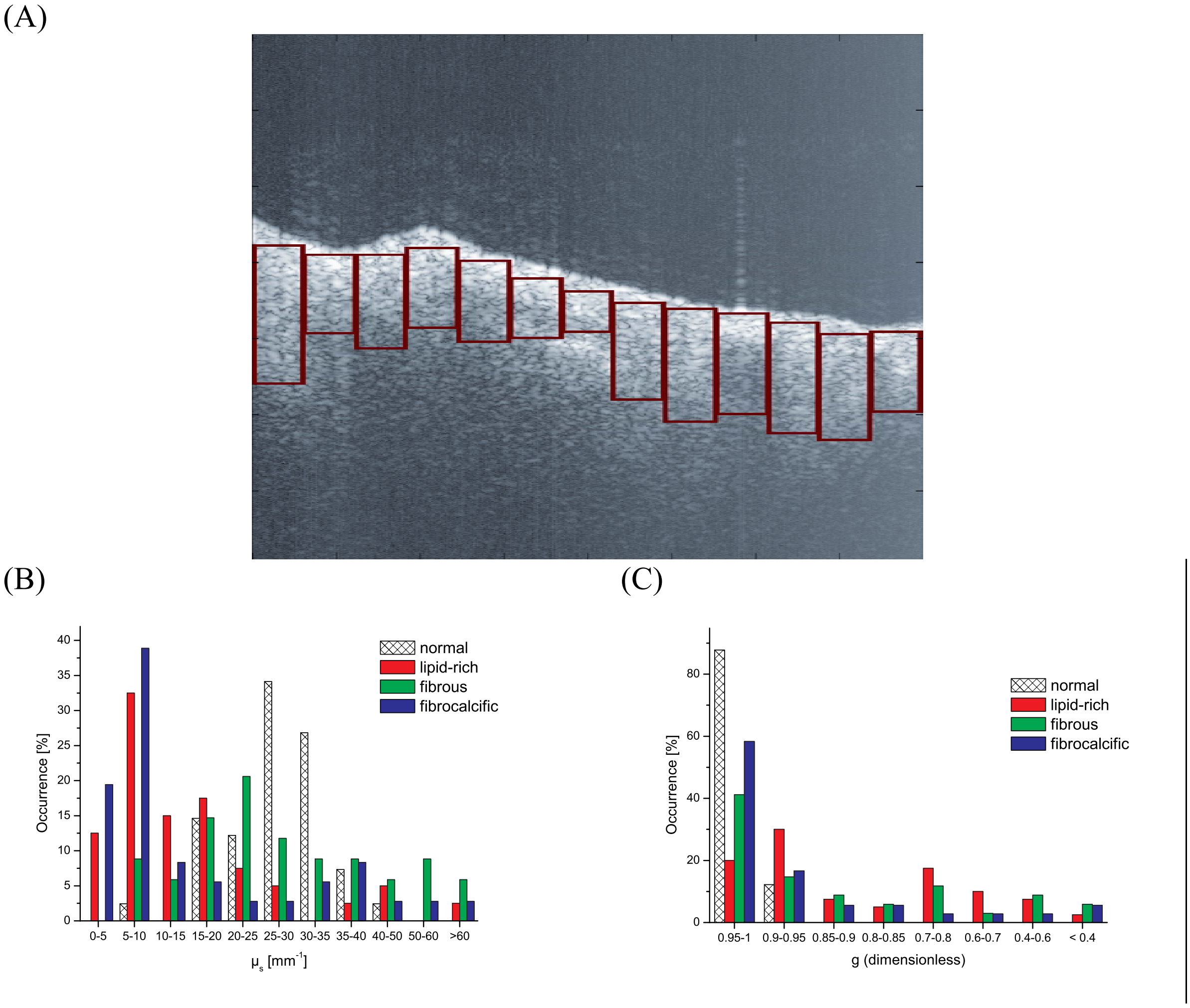

Figure 23. (A) Image of a lipid-rich carotid plaque subdivided into 13 ROIs. (B) and (C) display distributions of μ_s (B) and *g* (C) for normal arteries and lipid-rich, fibrous and fibrocalcific atherosclerotic plaques, respectively. In (B), μ_s for normal samples (striped) were centred between 15 mm^{-1} and 40 mm^{-1}, but were centred at lower values for lipid-rich (green) and fibrocalcific (blue) plaques, and were randomly distributed for fibrous plaques (red). In (C), *g* values were generally higher in normal intimas than in atherosclerotic lesions.

Future investigations will be concentrated on the following important issues: Firstly, to determine for which type of diseases our approach is applicable, e.g. atherosclerotic lesions or skin diseases. Secondly, for such lesions thorough studies establishing the relation between tissue pathology and optical properties should be carried out.

In summary, we have demonstrated an algorithm that based on adequate theoretical modelling is capable of extracting the optical scattering properties from OCT images. We have shown its capabilities experimentally and through numerical simulations. When applied to in vitro aortic specimens, our results suggested that lesion types could be differentiated by using this algorithm. We believe that this sort of functional OCT imagery holds promise for further increase of the diagnostic value of OCT.

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properties of highly-scattering media in optical coherence tomography images," Opt. Express **12**, 249-259 (2004).
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3.2.6 Extraction of optical scattering parameters and attenuation compensation in optical coherence tomography images of multi-layered tissue structures

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Two important applications of analytical OCT models with great potentials are (1) extraction of optical scattering parameters from OCT images, and (2) attenuation compensation. Extraction of optical scattering parameters from OCT images is a method to obtain more quantitative information from these images in order to improve the diagnostics, i.e. functional imaging. Attenuation compensation is a method to remove the attenuation caused by scattering in OCT images. This should improve the diagnostic capabilities due to a better differentiation of different tissue types.

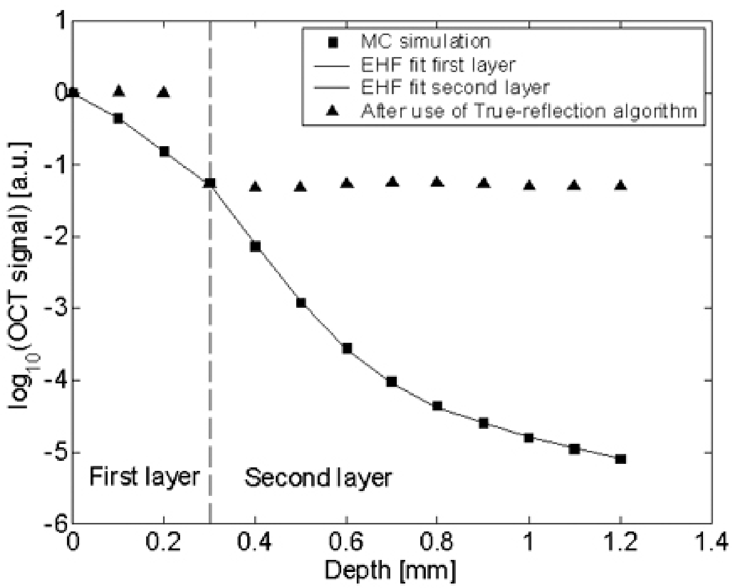

Figure 24. An example of an MC simulation of the OCT signal for a two-layer sample (squares) (μ_{s1} = 5.0 mm^{-1}, g_1 = 0.99; μ_{s2} = 10.0 mm^{-1}, g_2 = 0.92); EHF fit to the first and second layers (solid line); the MC simulation of the OCT signal after use of the true-reflection algorithm (triangles).

In a recent paper,[1] verification is given of a new method for multi-layer extraction of optical scattering parameters and attenuation compensation by expanding the OCT model developed by Thrane et al. based on the extended Huygens-Fresnel (EHF) principle.[2] In the verification, we use the Monte Carlo (MC) OCT model developed by Tycho et al.[3] to create a numerical phantom having a two-layer structure, i.e. to simulate the OCT signal from a two-layer tissue structure. A layer is here defined as a plane-parallel homogeneous region characterised by a scattering coefficient μ_s, an anisotropy factor g and an index of refraction n. We then fit the two-layer EHF expression for the OCT signal to the MC simulated signal, extract the optical scattering properties μ_s and g of each of the two layers, compare them with the MC input values, and use the extracted values of the optical scattering properties to correct for the attenuation caused by scattering.

An example of the MC simulation of the mean square heterodyne signal current is shown as squares in Figure 24. The fit of the two-layer EHF OCT model to the MC simulation is shown as a solid line in Figure 24. In general, excellent agreement is obtained between the extracted values for the optical scattering properties of the different layers and the corresponding input reference values of the MC simulation, which demonstrates its feasibility for in vivo applications, such as characterisation of vulnerable plaques. The MC simulation of the OCT signal after correction for the attenuation caused by scattering is shown as triangles in Figure 24. The distinct signal levels obtained for the two different layers after using the true-reflection algorithm strongly indicate that better differentiation of different tissue types may be obtained in OCT images of real tissue by using the true-reflection algorithm. This is expected to result in an improved diagnosis.

The project is being funded by the Danish Research Agency through The Danish Technical Research Council's grants no. 9901433 and 26-02-0020 (project BIOLASE).

1. L. Thrane, M. H. Frosz, T. M. Jørgensen, A. Tycho, H. T. Yura, and P. E. Andersen, "Extraction of optical scattering parameters and attenuation compensation in optical coherence tomography images of multi-layered tissue structures", Opt. Lett. **29**, 1641-1643 (2004).
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3.2.7 Doppler optical coherence tomography based on a field programmable gate array

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Optical coherence tomography (OCT) and Doppler OCT (D-OCT)[1,2] are subjects of much attention as this technique enables non-invasive measurement of tissue and blood flow mapping. Detection of the Doppler frequency is possible in various ways including known techniques from ultrasound. In D-OCT, a method based on analogue coherent demodulation followed by digitisation and subsequent signal processing has been demonstrated.[3] In other methods, the raw interferogram from the optical detector is digitised and digitally processed in a field programmable gate array (FPGA) followed by a digital signal processing (DSP) hardware unit[4] or entirely in a DSP.[5]

The scope of the present project is to design an FPGA to process optical Doppler tomography signals digitally. The processor fits into the analogue signal path in an existing OCT set-up.

In this project,[6] we demonstrate both Doppler frequency and envelope extraction using the Hilbert transform, all in a single FPGA. An FPGA implementation has certain advantages over a general purpose DSP due to the fact that the processing elements operate in parallel as opposed to the DSP that is primarily a sequential processor. In other words, in the FPGA the processing resources can be distributed in a manner optimal for the processing task at hand.

We demonstrate that the use of an FPGA enables sampling rates that exceed DSP-based solutions. Combined with use of a decimating digital filter this allows a simpler analogue anti-aliasing filter in front of the analog-to-digital converter. This implementation ensures high sampling rates without jeopardising the signal-to-noise ratio. The processing scheme is mapped to the FPGA resources by use of the CORDIC algorithm, which is an iterative algorithm for calculating trigonometric functions. It is well-suited to hardware implementations such as FPGAs because it does not require any multiplication operations, i.e. only the operations addition, subtraction and shifting are required. In addition, this implementation has the important feature that calculation of the phase in addition to the amplitude only requires few additional resources. The proposed implementation of Doppler frequency extraction in a single FPGA is feasible for real-time D-OCT applications requiring high signal sampling rates.

The FPGA processor was applied to the OCT system described in Ref. 7 to test the algorithms. A flow containing 2 % aqueous Intralipid solution through a capillary glass tube of inner diameter of 0.6 mm was used. The laminar flow could be varied from -80 to +80 mm/s peak velocity. The sample beam of the OCT system was incident at an angle of 69 degrees relative to the flow direction. This angle is the effective angle inside the fluid that, due to refraction, is different from the angle outside the capillary tube. The results of cross-sectional flow patterns for various flow velocities are presented in Figure 25.

It should be noted that the present implementation of the Doppler algorithm has been optimized for the velocity range in our experimental test set-up, i.e. the range -100 mm/s to +100 mm/s. In case the flow velocity range is much smaller, e.g. μm/s, as is the case for some tissues, the Doppler algorithm should be implemented to operate on a sequential A-scan according to Ref. 8. This is feasible using FPGA's described in this project maintaining the advantages discussed above.

The project is funded by the Danish Research Agency through The Danish Technical Research Council'sgrants no. 9901433 and 26-02-0020 (project BIOLASE).

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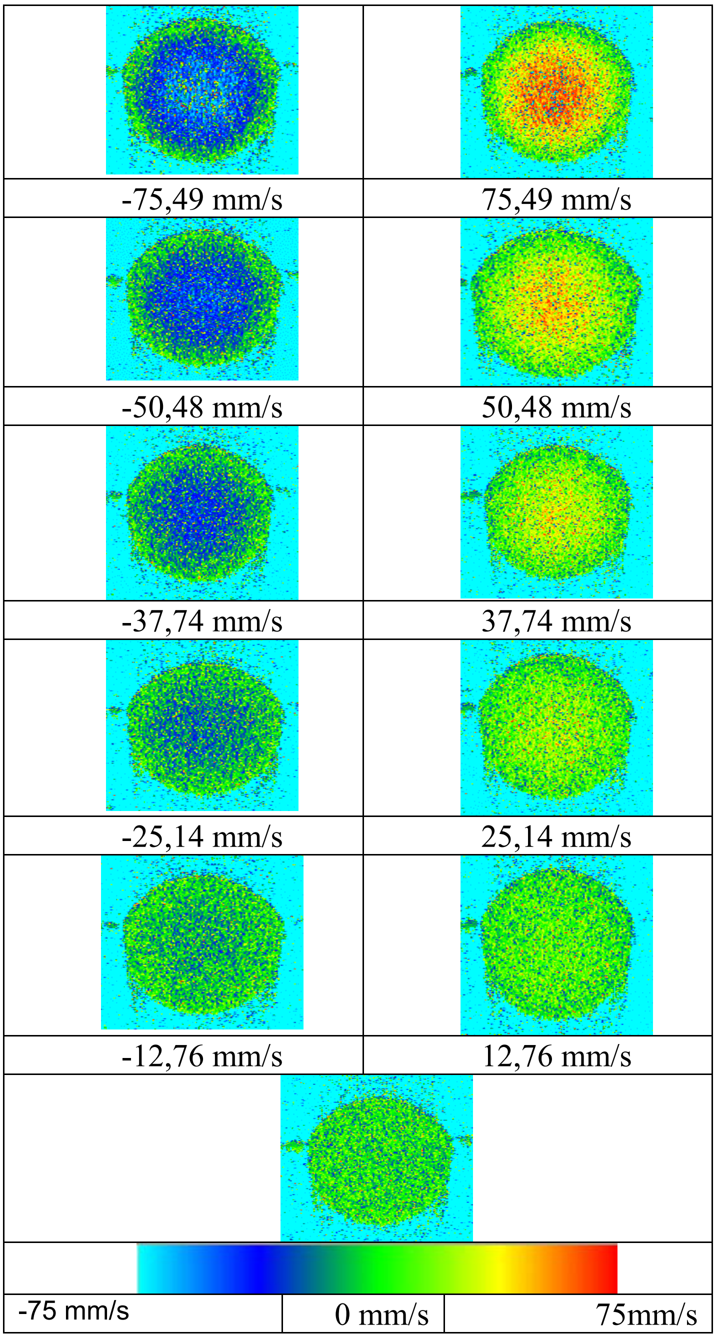

Figure 25. Flow profiles using the Hilbert and CORDIC. Flow velocity is peak velocity.

3.2.8 Dynamic contour model for aligning and segmenting images recorded with OCT

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The feasibility of using dynamic or active contour models for the alignment of OCT B-scans has been explored. The preliminary results indicate that this is a suitable approach for aligning neighbouring A-scans, from which a noise-reduced A-scan estimate can be produced. This average profile can then be used to extract optical parameters and/or geometrically discriminating features between different types of tissue.[1] In addition, the use of such image snakes can be used to segment out regions of interest such as the retinal nerve fibre layer in retinal OCT images. Border tracking algorithms are already part of commercial software packages associated with OCT equipment. However, the implemented routines do fail on images from time to time making it relevant for the medical doctors to access software where it is possible to interfere with the processing more directly.

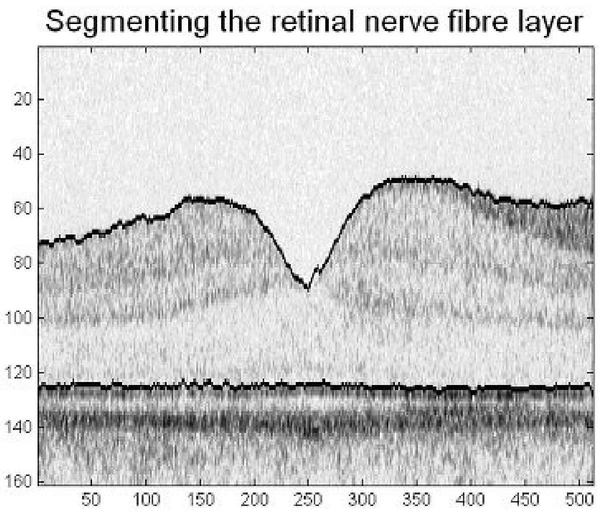

Figure 26. Segmenting the nerve fibre layer from a retinal OCT image using snakes and dynamic programming. Tracked borders are shown in black.

Swellings in the retina can be hard to detect from fundus images alone. Instead, using a number of radial and/or circular B-scans it is possible to generate a thickness map. For each B-scan two image snakes are used for segmenting out the nerve fibre layer.[2] One snake detects the retinal pigment epithelium surface, and the other snake detects the top layer of the retina. An example of the obtained borders on a retinal OCT image is illustrated in Figure 26. From the tracked boundaries we can calculate the thickness profile for the B-scan in question. Repeating this procedure for a number of radial and/or circular scans around the fovea and interpolating in between we can image a possible swelling. A generated thickness surface of a person with a macular edema can be seen in Figure 27.

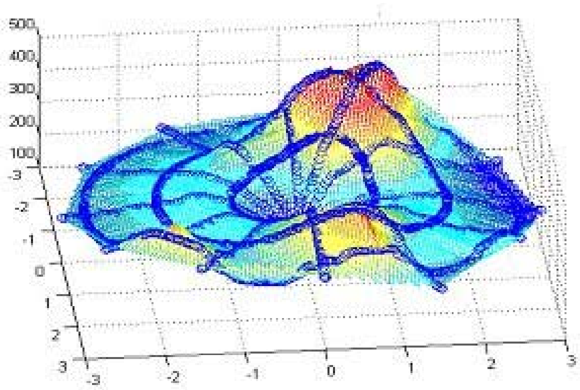

Figure 27. Retinal thickness map. Recorded points used to interpolate surface are contained on the dark web structure. The patient has a large macular edema.

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3.3 Infrared techniques

3.3.1 Infrared temperature calibration and related projects

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A reference laboratory for calibration of infrared instruments was established at Risø in 1996. Traceable calibration of infrared thermometers and blackbodies is offered in the temperature range -50 °C to 1600 °C. In 2001 the laboratory was approved by the Danish Accreditation Scheme, DANAK, to issue certificates for calibration of non-contact temperature measuring equipment.

The work affects the following main topics to reduce uncertainties of non-contact temperature measurements:

- Calibration service of infrared thermometers for customers;
- Temperature measurements for customers;
- Development of new and improved methods for infrared temperature measurements;
- Measurement of spectral emissivity of samples and coatings;
- Consultative service and information;
- International comparisons of standards and procedures;
- Design and construction of special blackbody sources for customers.

With the combination of high-accuracy traceable blackbody sources and spectral measurements of infrared radiation with FTIR spectrometer, Risø has state-of-art calibration capabilities in the spectral range from 1 – 25 µm. A powerful method has been developed for the measurement of spectral emissivity of samples, objects and blackbodies by an FTIR spectrometer.

Risø National Laboratory was evaluated and given status as national reference laboratory for non-contact temperature measurements in 2002. The nomination was given by the Agency for Enterprise and Housing based on an evaluation lead by the Danish Fundamental Metrology. As a national reference laboratory Risø shall:

- Disseminate traceable non-contact temperature measurements with the lowest uncertainty in Denmark under the accreditation of DANAK.
- Participate actively in national and international collaboration, carry out research and report in literature and at conferences.
- Maintain a broad knowledge of the field and communicate it to relevant institutions and users.
- Contribute significantly to the evolution of temperature metrology in Denmark.

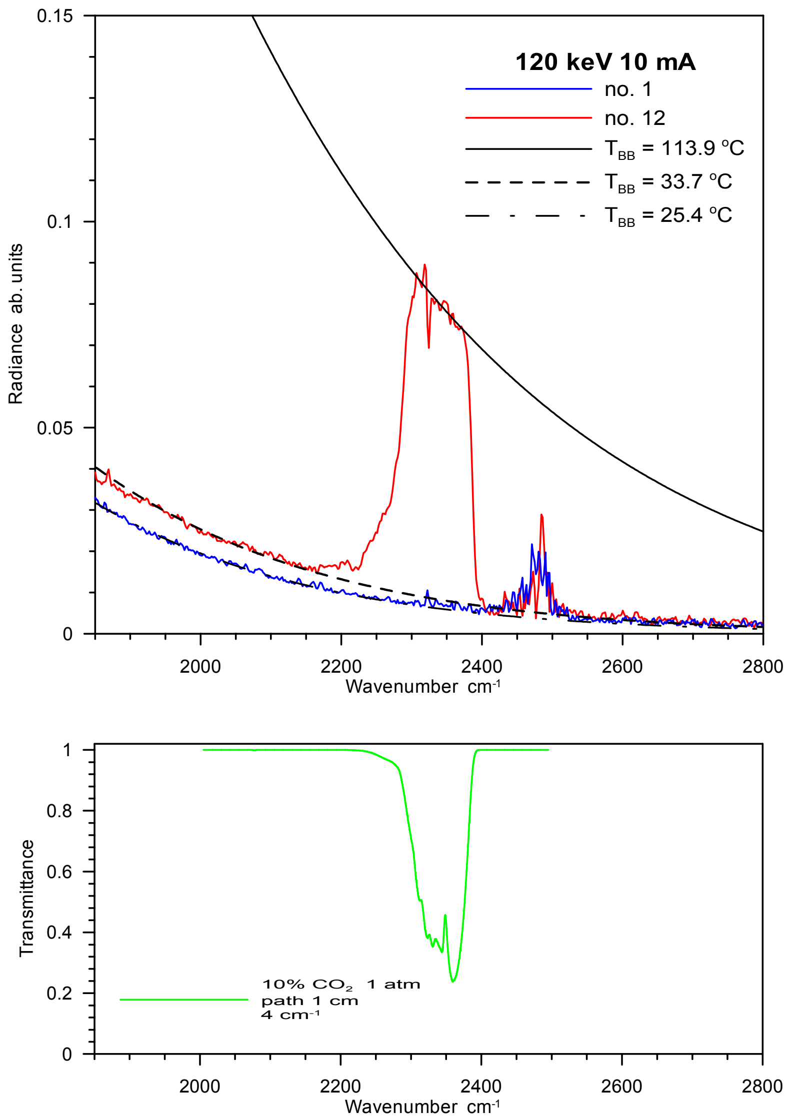

Figure 28. Example of FTIR gas temperature measurement at low temperature in facility run by the Radiation Research Department at Risø National Laboratory. Blue curve: Measured emission spectrum obtained using an IR-fibre before activation of beam. Red curve: Beam on for some seconds, background temperature raises (average temperature of surfaces) slightly, and the gas temperature increase is clearly seen (thermal radiation from CO_2). Green curve: Calculated (HITRAN database) transmittance spectrum for CO_2. Black curves: Best fits to Planck curves. Peak at 2450 – 2500 cm^{-1} is noise due to absorption band of IR-fibre. Spectra are collected with a resolution of 4 cm^{-1}. The work is planned to continue and will be published in 2005.

In the short term the nomination will strengthen Risø's contact with international project partners in the field, and will over time improve measurement capabilities. The nomination is an important highlight and points out the importance and quality of the work carried out by the temperature laboratory at Risø National Laboratory. Sønnik Clausen was selected to represent Denmark in EUROMET for the field temperature in 2004. In 2004 the laboratory has invested in new calibration facilities, a salt and a sodium heatpipe blackbody, to improve the best measurement capability in the temperature range 200 – 1070 °C. The new blackbodies are expected to be in operation in 2005. The activities in the national reference laboratory for non-contact temperature measurement follow the ISO 17025 standard. A report on the quality system at Risø has been prepared and was presented for QS-forum in Bucharest on 14-15 February 2005.

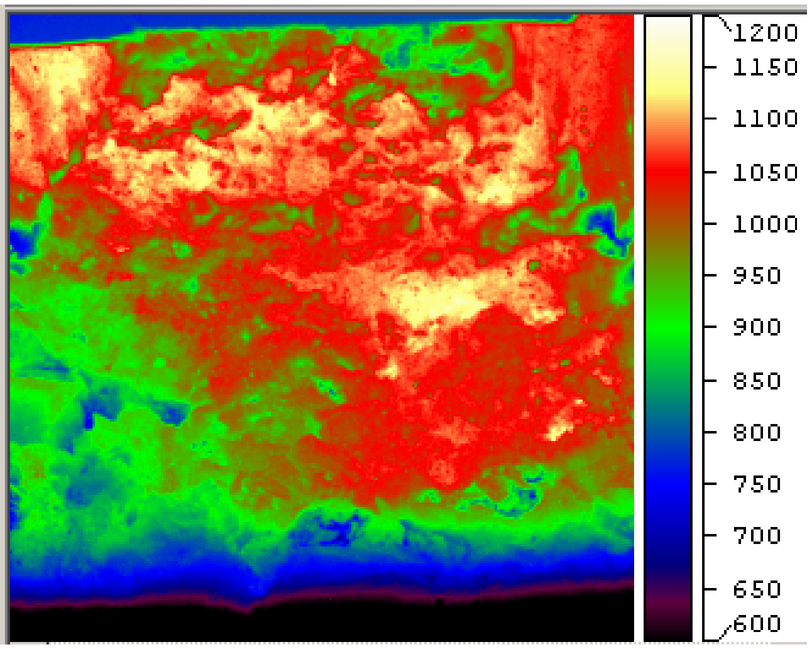

Figure 29. Temperature measurements for customer, example: Infrared picture of surface temperatures of burning waste layer on grate and furnace walls. Temperature peaks (white area left) cause damage to furnace walls. Result from experiment with Risø's IR-camera at Haderslev Kraftvarmeværk (a power plant in Jutland, Denmark). Furthermore, gas temperature measurements were performed in selected positions with a fibre optic probe by Risø National Laboratory to validate the temperature reading of IR-sensors installed.

Risø is involved in the EU project "EVITHEM" that started in 2003 with participants from laboratories from most of Europe. The overall objective of the project is to form a European virtual institute in thermal metrology.

A one-day course on infrared temperature measurement has been arranged as the result of cooperation with the Danish Technological Institute in Århus (Jutland) on technical courses for Danish industry.

3.3.2 MENELAS

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The goal of MENELAS is to develop innovative measurements and related apparatus that are capable of reducing time and costs for aeroplane engine development. These apparatus, with new technologies in accordance with present ICAO regulations, will bring to the aeronautics community original developments in infrared coherent sources specially designed for effluent trace detection in engine research and atmospheric impact studies.

The performance of the developed laser instruments in the project should be characterised through laboratory tests and cross calibration experiments prior to campaign measurements. In 2004 rhe Risø hot gas cell facility used in the AEROPROFILE EU-project for verification of methods based on FTIR spectroscopy was upgraded with a ceramic inner part to cover the needs in the MENELAS project.

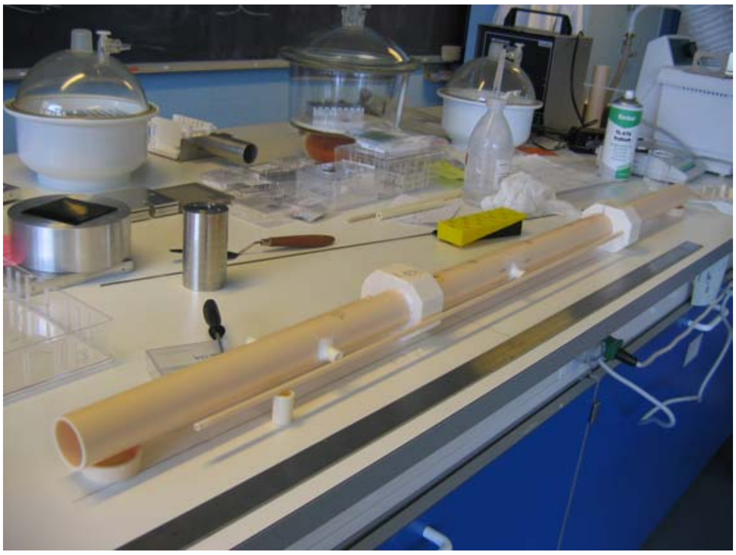

Figure 30. Picture of ceramic inner part to be used in Risø's hot gas cell facility. A technique developed for fuel cells is applied to obtain a gas tight mount of the sapphire windows. The ceramic gas cell was tested and function approved in experiments in 2004 (0-3 bar abs, 23 - 1100ºC).

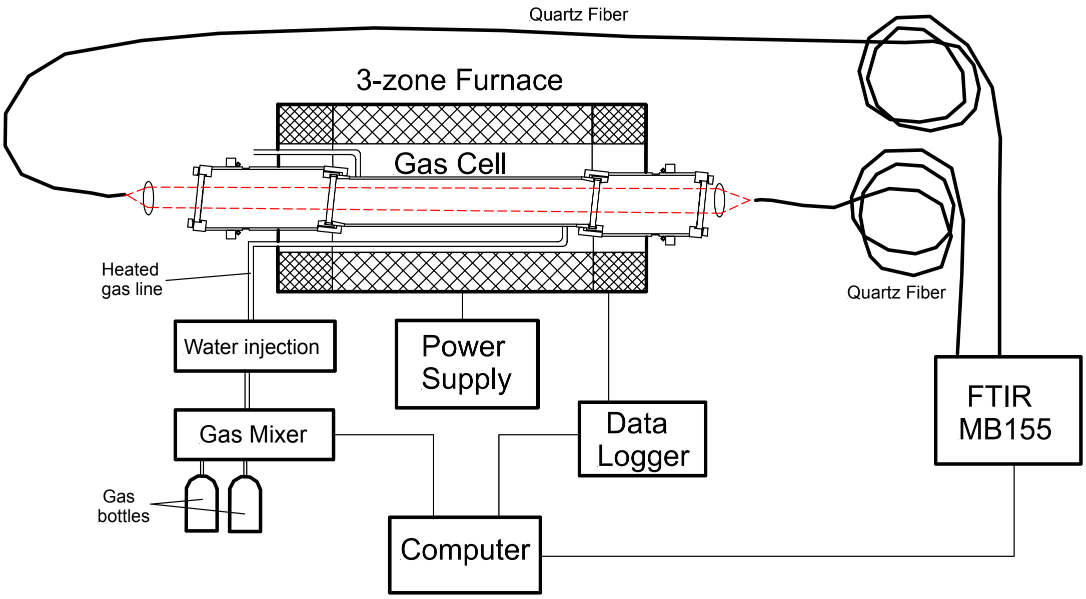

Figure 31. The hot gas facility at Risø. Experimental set-up in tests of upgraded hot gas cell. MIR (C2 chalcogenide) fibres were used in measurements with extended spectral range to cover fundamental bands of CO, CH_4 and CO_2. The temperature range is from ambient to 1373 K with gas cell windows of sapphire.

3.3.3 Surface temperature of deposit probe

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Deposit formation in biomass combustion may cause operational irregularities and problems such as corrosion of heating surfaces or decreased heat transfer conditions in the boiler. Deposit formation may be sought investigated on a laboratory scale in a solid fuel reactor of the flow reactor type, where in particular the temperature conditions in the reactor and on the deposit probe are targeted to be as realistic and well determined as possible. As a part of the biomass firing project, the surface temperature relations of the solid fuel reactor are investigated as a function of time and deposit evolution using an infrared camera. Moreover, for comparison Avedøre biofuel boiler (ABB) deposit temperatures at the superheaters are monitored using the same equipment and during straw combustion conditions. At ABB the superheater deposits are monitored to be 850 ºC – 1000 ºC, see Figure 32. This is significantly higher than in the solid fuel reactor, where the monitored deposit temperatures were 550 ºC – 710 ºC. For burning particle depositing on the probe and superheater, local excess temperatures are monitored that are around 90ºC - 150ºC higher than the temperatures of the superheater deposits. Further details can be found in Ref. 1.

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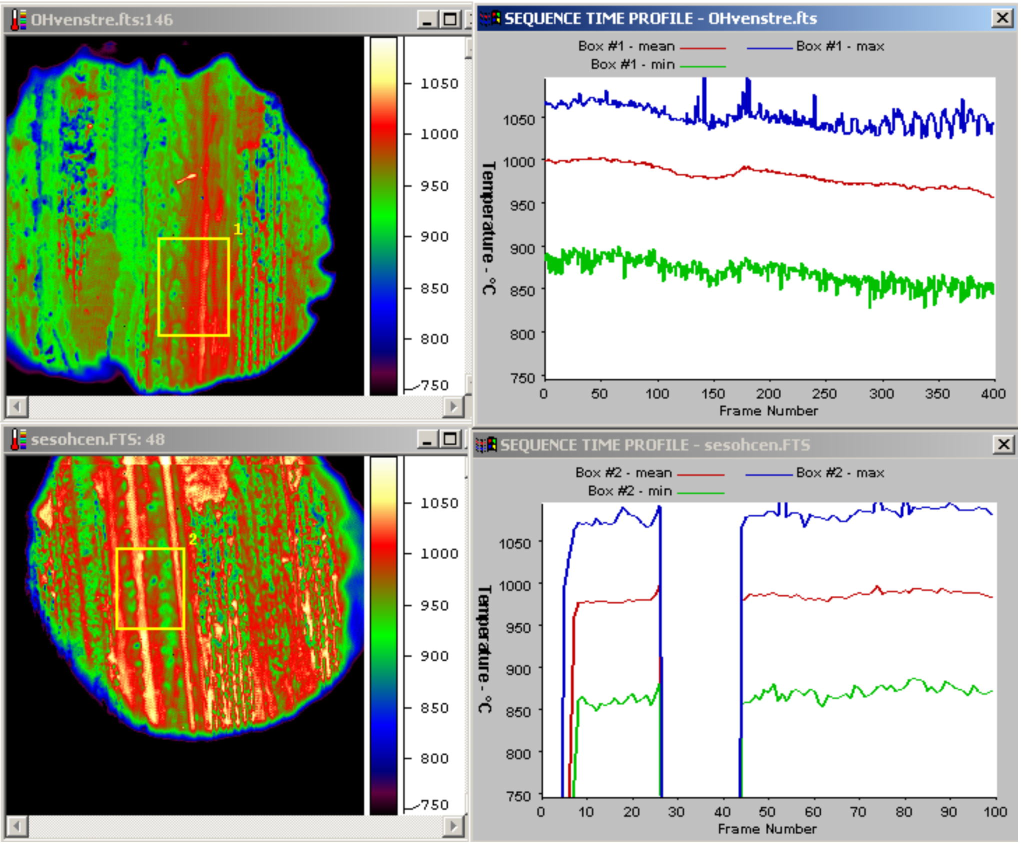

Figure 32. Thermo graphic picture of superheater in front of measuring port at Avedøre biomass furnace. Surface temperatures (right) is shown for marked area enclosed by yellow frame. Curves for maximum (blue), mean (red) and minimum (green) surface temperatures are given based on 400 pictures over 40 s.

3.3.4 Calibration of temperature measuring equipment

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The temperature range of accreditation is –196 to 1600 °C. In addition to calibrating temperature measuring equipment, the laboratory calibrates electrical and pressure instruments in a smaller range.

During calibration of temperature instruments, problems with the instruments are often detected. These problems are investigated when possible. One of this year's investigations is test of block calibrators.

The Thermometry Laboratory at Risø National Laboratory has measured on dry block calibrators since the first prototype was developed in Denmark more than 25 years ago. It has always been known that the block and the insertion part have a problem with temperature difference in the axial distribution. Risø National Laboratory has therefore always written the thermometer type used and the length of the sensor in the certificate, Rosemount 162CE with a sensor length of 50 mm.

Three types of calibrators have been tested: the low range block from –40 to 140 °C, and two different types of blocks for the high range from 50 to 650 °C. This work describes common problems using block calibrators and is not only related to the tested brands. The tested block calibrators are some of the well-known brands on the market.

Measurements at Risø National Laboratory show, that it is possible to calibrate three thermometers of same type (Rosemount 162CE) in the same multihole insertion and to get as small differences as 3 mK at 100 °C, 8 mK at 400 °C and 18 mK at 650 °C even though there was a temperature difference of more than ±0.4 °C in the axial distribution. The same block calibrators and the same multiinsertions were used when the calibrators were tested for the temperature differences in the axial distribution after the EA 10/13 procedure, and here the differences were ten times bigger than mentioned above. The first measurements, using the Rosemount thermometers, more show that the manufacturer of the Rosemount 162 CE is making their thermometers with the same size of sensor every time than the calibrators are good for the small uncertainties.

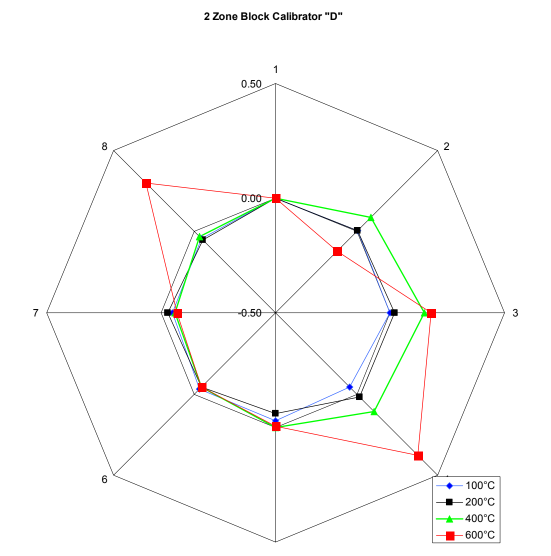

Figure 33. The temperature distribution in the horizontal plane.

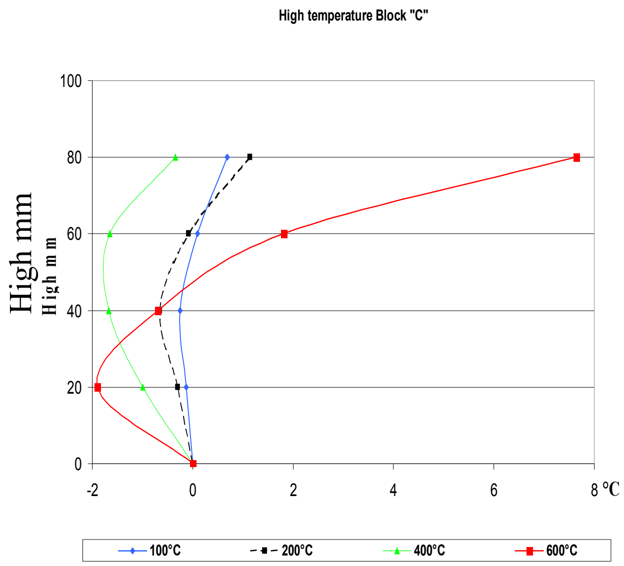

Figure 34. The temperature distribution in the axial plane.

Figure 33 and Figure 34 show the temperature distribution in the axial and the horizontal planes, in a multihole insertion. More details can be found in the total paper from "Tempmeko 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science", "*How to use a blokcalibrator to obtain the smallest uncertainties*", by Finn Andersen.

3.4 Optical sensors

3.4.1 Miniaturisation of optical sensors

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Technologies providing low costs, miniaturisation and high reliability are essential for optical sensors[1] in order to find commercial interests for industrial applications and products. Within the Centre for Miniaturizing of Optical Sensors (MINOS) (http://www.sensortec.dk/stc.htm), concepts of such micro-optical sensor systems were studied. After finishing MINOS in 2003, related and new concepts and designs have been developed with new commercial contacts to the point of having alpha-prototypes ready for performance tests.

The main achievements in 2004 have been the development and testing of three optical sensor designs, all based on a technology that combines the phenomenon of laser speckle translation with spatial filtering velocimetry.[2] This enables the sensors to measure in-plane linear translation or out-of-plane rotation of rigid bodies in real time, and with calibration factors being independent of the optical wavelength. Combined with new commercial micro-optical components or replications of these in polymers, and vertical cavity surface emitting lasers (VCSELs), these optical sensors can be produced in compact versions, yet as robust and low-cost devices.[3] Furthermore, laser safety can be incorporated in the optical design, and even improving the sensor signal.

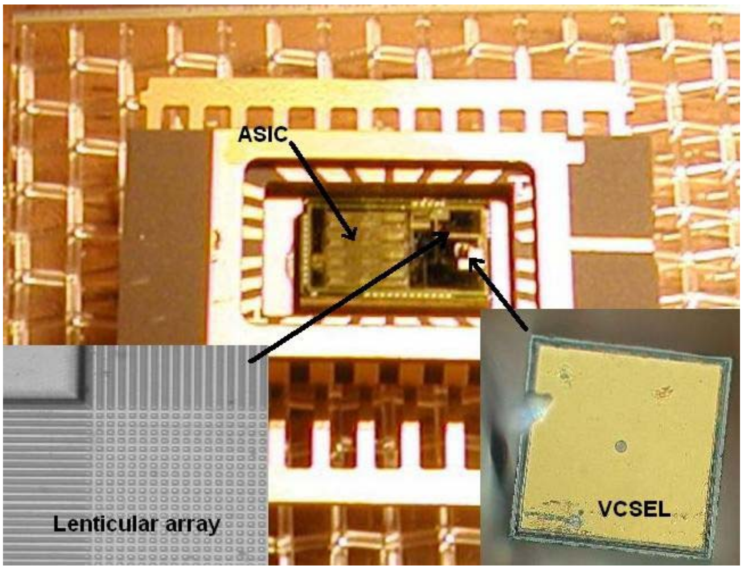

Figure 35. An exploded picture of the optical displacement sensor: The VCSEL forms the speckles and is mounted on the ASIC. The optical spatial filter is based on micro-lenticular arrays and microlenses, and is positioned a couple of mm above the ASIC. The ASIC contains the photodetector arrays and carries out the initial signal processing.

The displacement sensor[3] measures linear displacement of the target surface in two dimensions, and is integrated in a chip housing together with an application specific integrated circuit (ASIC) chip in a new concept for optical navigation (see Figure 35). Compared with a traditional optical mouse, this technology provides lower production costs, higher counting rates (1600-2500 cpi) and an extended range of applicable target surfaces (e.g. smooth and glossy surfaces, and even skin).

The rotation sensor[4] measures rotational velocity of a shaft with high measurement accuracy, and without influence from the target radius, drift in optical wavelength and any target translation. The sensor does not require any preparation of the target, and can be applied to any target (any radius and finish) with a non-specular surface. The sensor has been applied to various test set-ups with the intention to measure fluctuations in angular velocity. When measuring single events with an angular resolution of 2 degrees, the accuracy is 0.7 %. When measuring over, e.g., nine periods of a repeated event applied to a rotating target with a higher cycle frequency, the sensor easily measures fluctuations down to 0.01% of the mean angular velocity.

The vibration sensor – designed around the same basic idea – has shown to be capable of measuring in-plane translational or out-of-plane rotational vibrations of a solid object in real-time with a resolution of a few nanometres within a bandwidth of 170 kHz.[5]

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3.4.2 Phase singularities in analytic signal of white-light speckle pattern with application to micro-displacement measurement

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We have proposed the application of phase singularities,[1] to optical metrology. In contrast to the common belief in phase unwrapping where the phase singularities are considered as obstacles or nuisances in optical metrology, we have suggested a new approach for making use of phase singularities in optical metrology.[2] Preliminary experiments have been performed that demonstrate the validity of the proposed technique. We have given a mathematical analysis to the variation of the density of phase singularities with a lateral shift introduced to the analytic signal of the speckle pattern.

The high sensitivity for measuring lateral displacements of speckle patterns was achieved by converting an incoherent image into an analytical function by using the Hilbert transform. The pseudo-phase thus obtained is used as the object and the density of phase singularities as a function of the laterally induced translation of the displaced pattern with respect to the nondisplaced one is recorded. It has been shown, see Figure 36, that a sharp minimum in the number of phase singularities is observed when the net displacement equals zero.

In this preliminary work, we have not yet clarified the potential and the limitation as well as the practical advantage of the proposed technique over the conventional intensity correlation speckle metrology. However, we should stress that the aim of this preliminary paper is to point out the possibility of making use of phase singularities in optical metrology, which we believe to be novel and worth exploring. In early time, speckle patterns were regarded as a nuisance that degrades image quality, but now the speckle patterns are well appreciated as a very useful vehicle for optical metrology. Learning from history, we consider that phase singularities that are now regarded as obstacles in phase unwrapping will also become very useful vehicles in optical metrology. The proposed technique may serve as an initial example of optical vortex metrology to be further developed in the future.

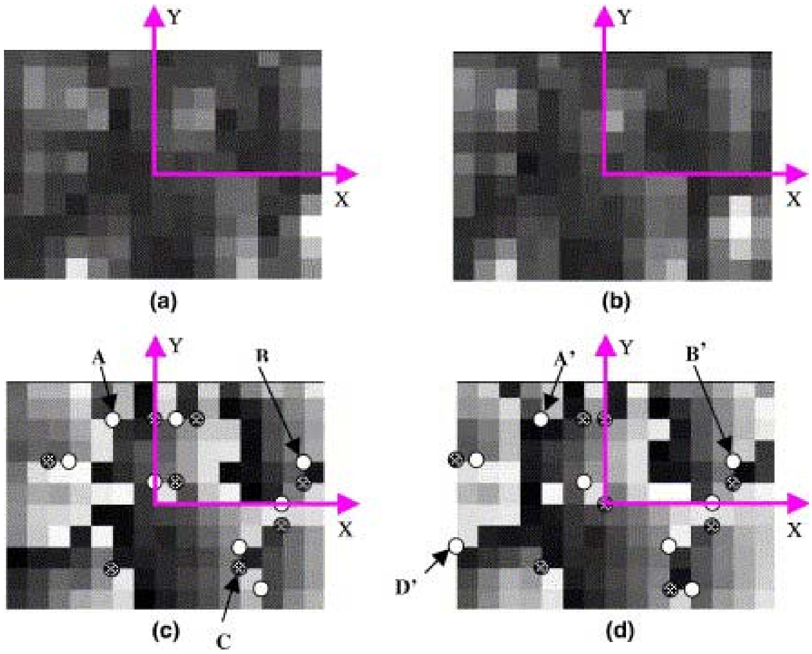

Figure 36. (a) Intensity distribution of white-light speckle pattern for the object before displacement. (b) Intensity distribution of white-light speckle pattern for the object after displacement. (c) Wrapped pseudo-phase map for analytic signal of (a); (d) wrapped pseudo-phase map for the analytic signal of (b). The open circles and filled circles indicate the locations of positive and negative phase singularities; the unprimed and primed alphabets indicate the correspondence between the phase singularities before and after displacement, respectively.

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3.4.3 Role of caustics in the formation of networks of amplitude zeros for partially developed speckle fields

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The topology of a partially developed speckle field has been studied by use of interference techniques through computer simulation. Amplitude and phase structures in the vicinity of caustics for a coherent radiation field scattered at a surface with large inhomogeneities have been investigated.[1] It was confirmed that the caustics are indispensible components of the procedure for the formation of networks of amplitude zeros for a coherent field scattered by a rough surface with large inhomogeneities. It has been shown that the formation of interference forklets in the field gives evidence of changes in the topology of the field, as these forklets are a diagnostic sign of transition from a caustic to a three-dimensional pattern of a diffraction catastrophe.[2]

The singularities for an optical field are described by the intersection of the curves for the real and the imaginary parts of the field

$$\mathrm{Re}[A(x,y)] = 0 \text{ and } \mathrm{Im}[A(x,y)] = 0\,. \tag{1}$$

Computer simulations have been performed in accordance with a previously described method.[3] Figure 37 depicts the birth and annihilation of dislocations, which gives evidence of changes in the topology of the field, thus creating a valuable tool in the description of the interaction between the surface and the field.

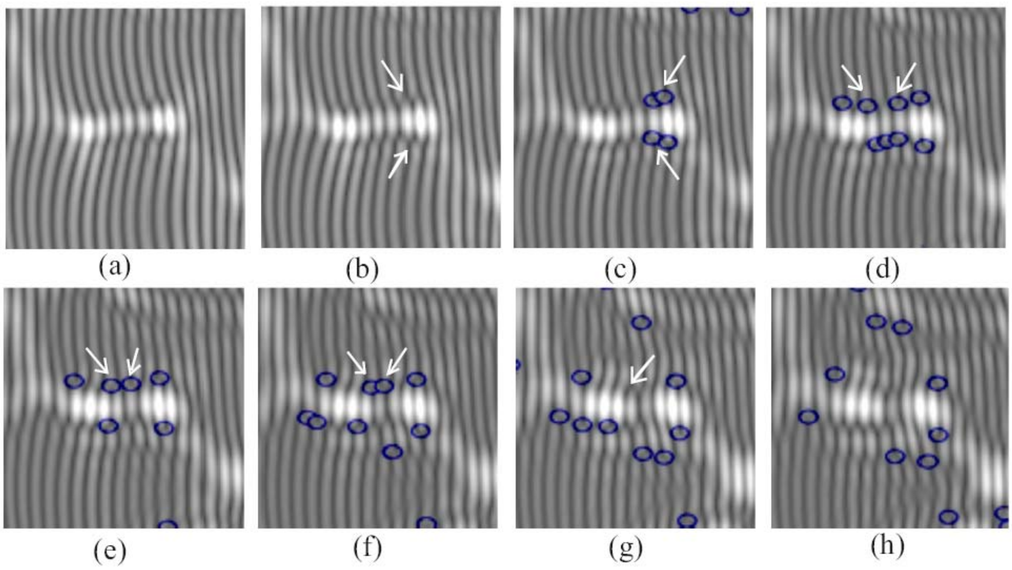

Figure 37. Fragments of interferograms of the field at distances (a) z_1 = 7 µm, (b) z_2 = 8 µm, (c) z_3 = 9 µm, (d) z_4 = 10 µm, (e) z_5 = 11 µm, (f) z_6 =12 µm, (g) z_7 = 13 µm, and (h) z_8 = 14 µm from a rough surface. Amplitude zeros have been marked by circles. One can observe (c), (d) birth and (g) annihilation of dislocations marked by arrows.

In summary, we have proposed to use the interference approach to investigate the development of singularities in a coherent field scattered by a rough surface with large inhomogeneities, as a function of the distance to the observation plane. This approach, based on computer simulations, provides results that are similar to the results of laboratory experiments. We have demonstrated the feasibility of studying mechanisms and peculiarities of the development of complex speckle fields and their amplitude and phase structures at various scale levels and at various registration zones. We have applied interference techniques to diagnose phase saddles for the optical field. Known situations that are favourable to the formation of partially developed speckle fields with inherent singularities have been confirmed and demonstrated. The mechanisms of transformation of a developed speckle field structure that results in changes of topology have been investigated. We have confirmed that caustics are indispensable components in the formation of networks of amplitude zeros for coherent fields scattered by rough surfaces with large inhomogeneities. It has been shown that caustics are the centres of formation of clusters of amplitude zeros for a partially developed speckle field.

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3.4.4 Wavelength stabilisation of CO_2 laser by measuring only the power supply

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The general objective of the project is to improve the market position of wind power by enhancing the credibility by more accurate performance assessment of the wind turbines.

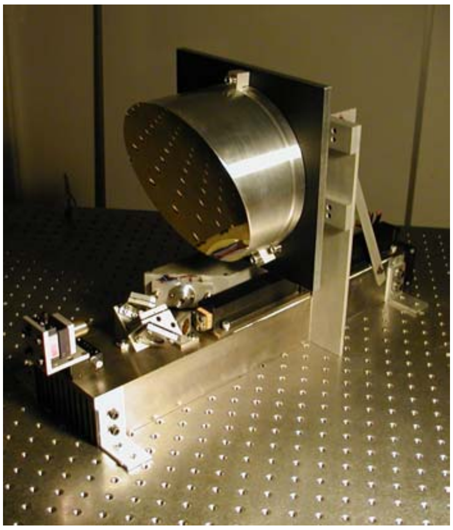

Figure 38. The optical assembly for the laser anemometer. The long black rod is the waveguide laser. The unit with the cooled detector and the low noise amplifiers can be seen mounted on the rear side of the laser heat sink underneath the large telescope mirror.

A laser anemometer to measure wind velocity in front of a wind turbine has been built by the Optics and Plasma Research Department at Risø. Instead of using a cup anemometer mounted on a tower, a laser anemometer is found to constitute a more flexible instrument for performing measurements of the wind velocity in front of the wind turbines.[1] The laser anemometer is intended to be mounted on the top of the nacelle and focuses a single laser beam in front of the wind turbine. The velocity of the wind is determined by measuring the introduced Doppler shift of the laser light, scattered backwards from the airborne aerosols in the focused laser beam. The measurement should be performed so far away that the measured wind is unobstructed by the turbine.

The instrument is based on a CO_2 laser with an invisible optical wavelength of 10.6 μm. The laser is a sealed waveguide laser and has been specially designed for the laser anemometer in cooperation with Ferranti Photonics, Scotland.

The CO_2 laser is not actively cooled, nor temperature stabilised. The temperature of the laser therefore depends on the temperature of the heat sink and thereby on the ambient temperature. The working wavelength of the freely running laser changes with temperature which affects both the emitted laser power and the coherence properties of the laser radiation. An alternative stabilisation scheme has been implemented to stabilise the laser wavelength. Instead of measuring the optical power output of the laser, which adds an extra detector to the optical set-up, the stabilising circuit makes use of the correlation existing between the power of the optical laser output and the standing wave ratio, SWR, which is theratio of the RF power transmitted by the laser power supply to the power reflected back from the laser unit. The stabilisation electronics is implemented by using digital signal processing.

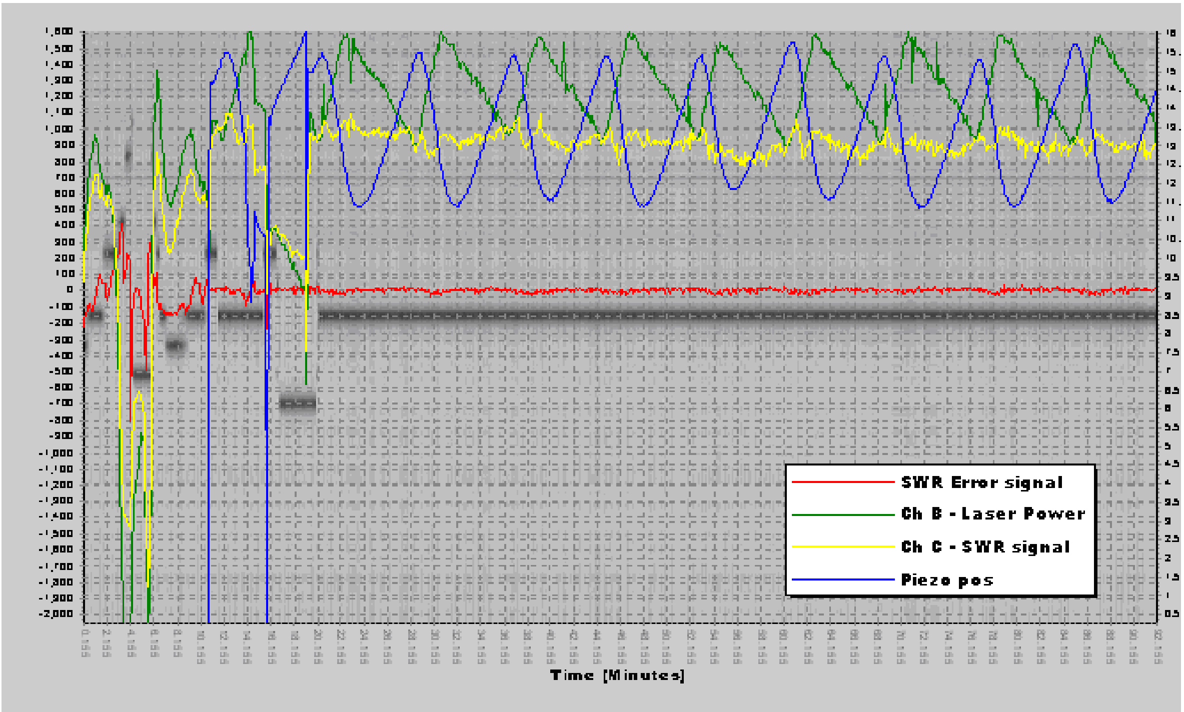

Figure 39. Stabilization of the CO_2 laser. First the freely running laser and then the stabilised laser. The background of the plot shows the spectrum of the laser output with time. With the freely running laser, the correlation between the laser power and the SWR-ratio is clearly seen. The laser can afterwards be wavelength stabilised by using the gradient of the SWR signal (the SWR-error signal) as can be seen on the last part of the plot. The back mirror of the laser cavity has been mounted on a piezoelectric element to adjust the cavity length. The measurement shown is with a water-cooled laser, and the period of the variations of the laser power (and position of the piezo-controlled back-mirror) corresponds to the switching the water cooler on and off. As can be seen, the wavelength is stabilised even when the laser power varies slightly with temperature.

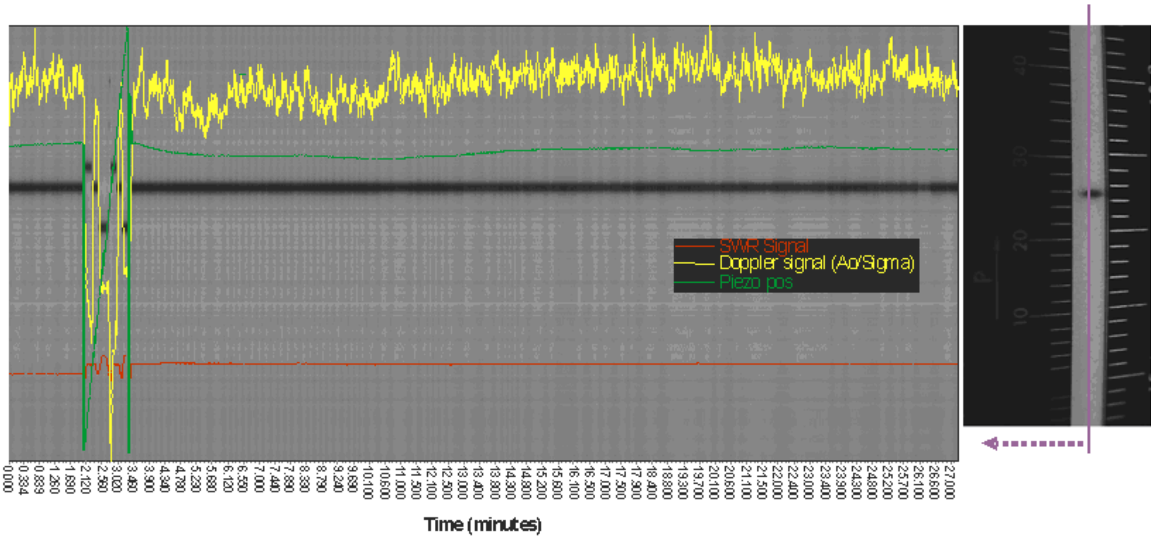

Figure 40. The stabilisation of the CO_2 laser. The image line of the spectrometer, included as the background in the plot, is shown on the right-hand image. First the laser is scanned for optimum Doppler signal. After the scan, the laser is locked to the line found with the best Doppler signal level.

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3.4.5 Single-frequency, high-power tapered diode using phase-conjugated feedback

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For many applications such as frequency doubling, high-resolution spectroscopy or LIDAR, a high-power, single-frequency light source with good spatial properties is needed. Here we demonstrate a novel design that can meet these demands. The system is based on a tapered diode laser in an external cavity design with a phase conjugating medium. Phase-conjugation has for long been recognized as an attractive method of correcting beam distortion and improving the spectral features of high-power lasers.[1]

The tapered diode with the external cavity set-up is shown in Figure 41. The tapered diode laser itself consists of a narrow section with transverse dimensions supporting only a single spatial mode. The single-mode section is followed by a tapered section that acts as an amplifier for the optical output from the first single-mode section. The basic idea of our external cavity set-up is that the standing wave in the external cavity induces an interference filter through two-beam coupling in the phase-conjugate medium. The generated filter now acts as a narrow band reflection filter that suppresses secondary lasing modes from reaching the threshold of lasing.[2]

Using the described method, an output power of 1.6 Watts, at 785 nm, has been obtained. To our knowledge this is the highest output power reported from a diode laser using phase conjugation. The line width was measured to be less than 2 pm (the measurements were limited by the instrument resolution), see Figure 42. The line width shown is at least 3 orders of magnitude smaller compared with the standard diode lasers.

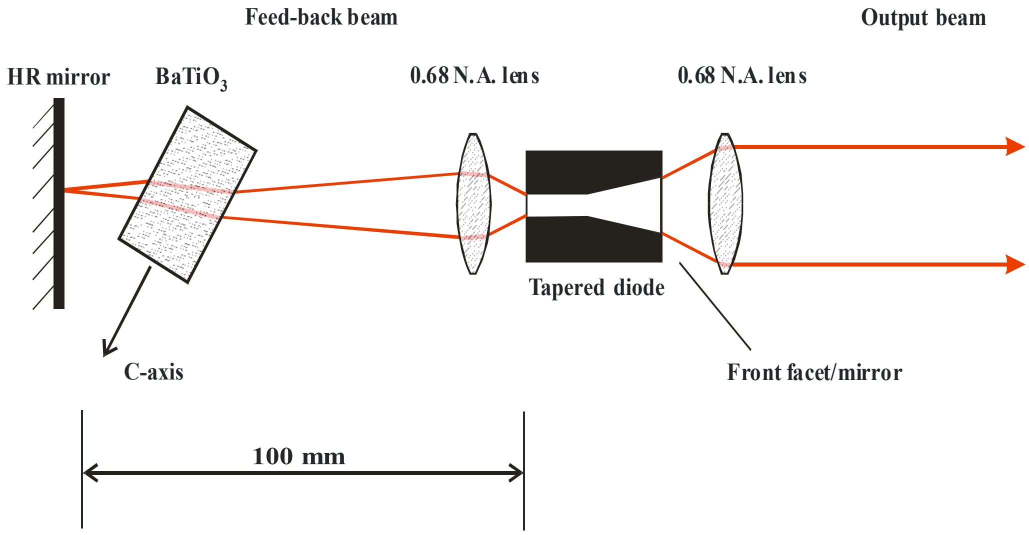

Figure 41. Schematic presentation of the optical set-up using a tapered laser diode.

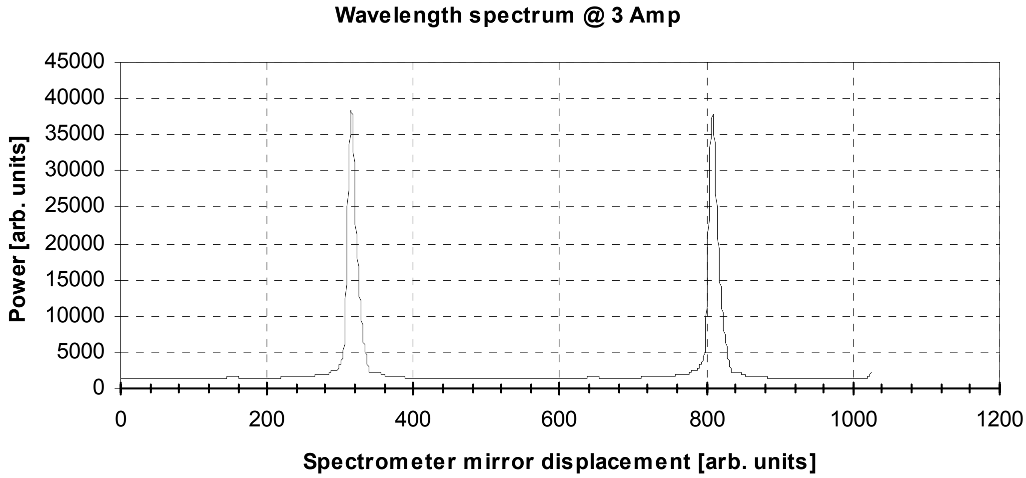

Figure 42. Spectrum of the optical output from the diode laser set-up with the combined phase-conjugating crystal/mirror external cavity feedback.

Since the phase conjugator acts as an adaptive element, this laser operates single frequency at all power levels. This is in contrast to passive frequency-selective elements like etalons or gratings. The well-known self-scanning phenomenon is avoided[3] when the phase conjugator is placed close to the rear end of the mirror.

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3.5 Generalised phase contrast method and its applications

3.5.1 "4D" optical manipulation based on the generalised phase contrast method

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Sculpted light fields have advanced our ability to manipulate colloidal aggregates and brought unique opportunities for fundamental and applied science.[1] From a physical stance, tailored optical potentials have been used to investigate underlying mechanisms of optically bound matter, stochastic resonance in Brownian particles, and light-matter angular momentum transfer. Of technical scientific significance are the novel applications of optical manipulation for powering colloidal micro-fluidic machines,[2] assembling templates for epitaxial crystal growth and fractionating mixtures through optical lattices.[3,4] Solely relying on optical forces, arrays of microscopic objects have been patterned in one, two and three dimensions. In particular, material engineers have seen the potentials of optical manipulation in synthesising advanced materials. This has been substantiated in recent works showing the complementary role of optical trapping with laser-initiated photo-polymerization for the construction and gelling of permanent particle arrays from linear to crystal-like structures. Aside from the ability to form pre-defined structures in 3D, however, a number of applications, including those of biological relevance, would significantly gain from the power of being capable of arbitrarily adjusting the relative positions of particle aggregates over a full volume and in a manner that satisfies real human or biological response time.

With the advent of spatial light modulators (SLMs), rapid developments boosting the degree of control for optically trapped particles have been seen in two techniques based on diffractive optics[1] and the generalised phase contrast (GPC) method.[5,6] Previously, we have shown the suitability of the GPC-approach for direct and user-interactive manipulation of a colony of cells to be analysed and large dynamic range in position control as its primary advantages.[7-9] Besides, we have implemented the GPC method in a novel and light-efficient configuration resulting in a purely optical 3D spatial confinement of trapped particles.[10] Using a robust polarisation scheme,[11] we have moreover demonstrated simultaneous control in the axial position of a group of trapped particles through variation of the relative powers of orthogonally polarised beams confining the individual objects.

Up until today it has only been possible to interactively manipulate a few particles or a small but fixed group of particles. In a recent Nature review article,[1] the emphasis was on the latest achievements of holographic optical tweezers (HOT) for manipulating groups of particles in pre-calculated geometries. Recently, we have reported at the SPIE annual meeting in Colorado, that GPC-based optical manipulation can perform exceptionally compared with the HOT approach. In fact, we have demonstrated by far the largest scale *true real-time user-interactive* manipulation in 3D space of a plurality of particles found in the peer-reviewed science today, which we have coined '4D user-interactive multi-beam manipulation'.[12] In addition, we have demonstrated that an ensemble of living cells can be readily manipulated in 4D while they are still dividing. This is also "a first" and a key aspect for real-world applications in micro-biotechnology, biophotonics and for all-optical lab-on-a-chip implementations. We have applied the concept in a simpler version together with leading cell scientists in Denmark to investigate advanced growth phenomena in mixed populations of living cells. This work has just been submitted for publication and the exciting details of it will soon be disclosed.[13]

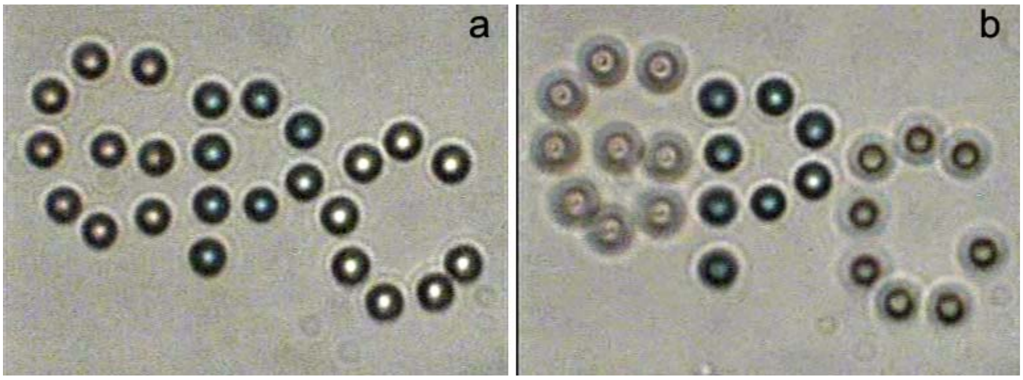

Figure 43. User-coordinated patterning of commercially dyed polystyrene micro-beads in (a) 2D; and (b) 3D, forming the text “GPC”, using a distinct bead-colour in each character.

The GPC-based 4D manipulation creates a myriad of micro-thin beams of laser light and each beam can trap and independently manipulate a microscopic object simultanously with all the others. The versatility of the GPC-approach is reflected by the fact that a user can specify the number, the size, the shape, the intensity, the spatial position and the speed of each beam independently by using a computer mouse attached to a simple laptop. This opens the door for a range of new applications within bio-, materials-, micro- and even nano-scale technology, among which several have never been possible before. One obvious application is to implement an ”all-optical lab-on-a-chip” to non-invasively investigate the growth behaviour in large cell colonies while maintaining natural growth conditions using sculpted laser light in the near-infrared.

Figure 43 and Figure 44 illustrate some of the possibilities of the 4D GPC-system to allow access into new exciting experiments involving well-patterned or dynamically driven systems of colloidal particles, including colloidal arrays created as analogues for modelling systems that are irrepressible or inaccessible within atomic and molecular domains. For microbiologists, it serves as a non-invasive tool for manipulating cells into spatial configurations that may trigger variations in developmental features. Over other alternatives, the GPC-approach offers several advantages. Further scaling of the real-time user-interactive manipulation to very large-scale particle arrays (hundreds of particles) is feasible since GPC can in theory reconstruct fully dynamic arbitrary arrays with close to 100% efficiency requiring no computational overhead, which is compulsory in a DO-based approach like HOT.[1] Using GPC, trap resolution may be set equal to SLM resolution, and the lateral intensity distribution that forms the trapping patterns can easily stretch along the extent of the whole microscopic field of view. In comparison, photon efficiency in a DO-based system depends strongly on spatial trap locations, array geometry and symmetry and is compromised by the limited space-bandwidth product of the SLM and by the unwanted zero-order and higher-orders accompanying any desired diffraction pattern.

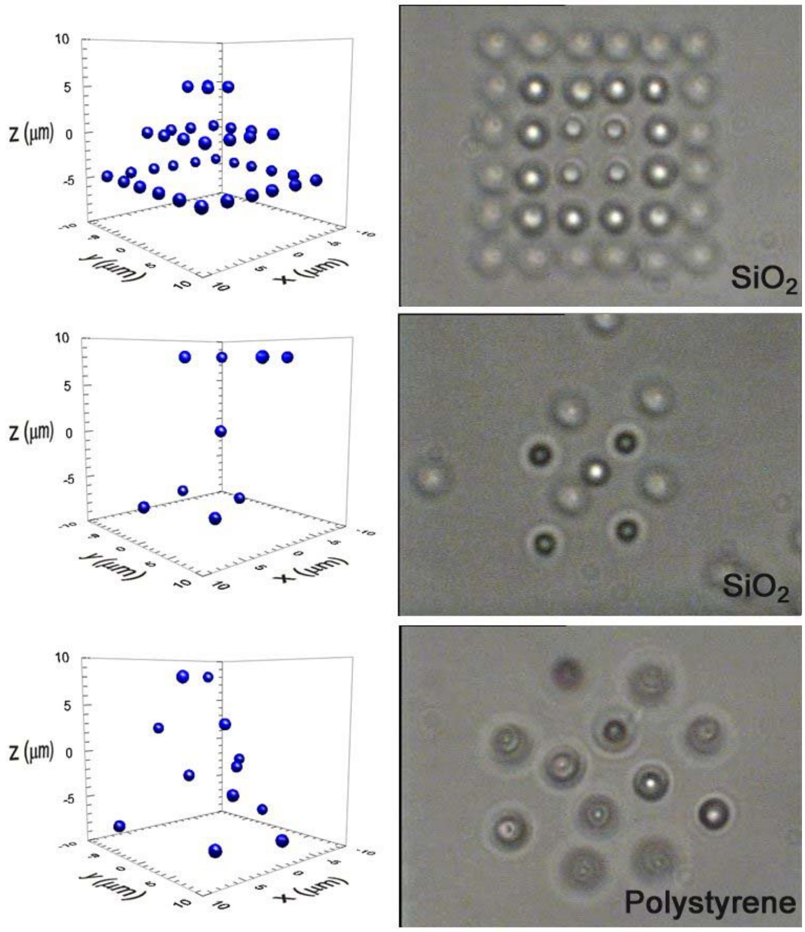

Figure 44. GPC-based trapping and user-interactive manipulation into arbitrary constellations of colloidal structures. 3D rendered views of the micro-particles relative positions are shown to the left.

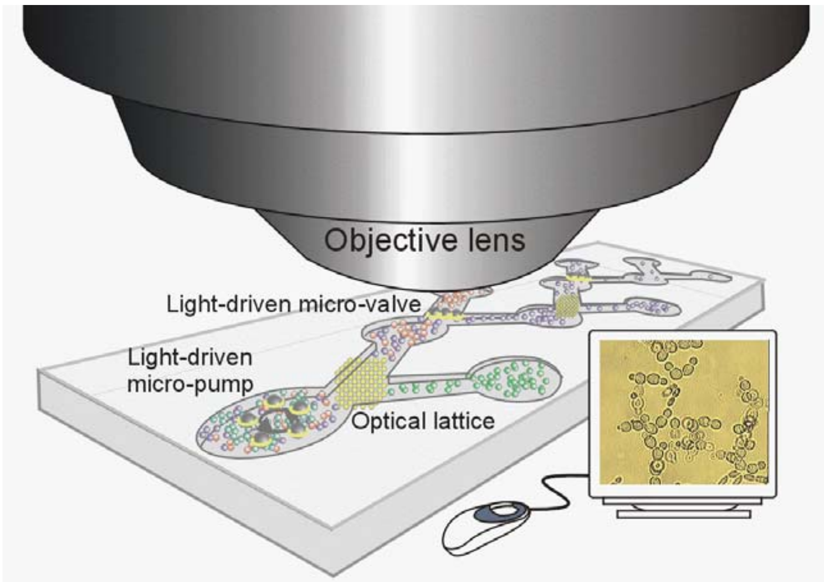

Figure 45. An 'all-optical lab-on-a-chip' concept. Using spatially sculpted light a user can assemble structures, perform optical fractionation and control the functionality of light-driven pumps, valves and mixers inside micro-fluidic channels. These multiple and dynamic functionalities can be controlled simultaneously through a computer interface.

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3.5.2 GPC-based manipulation of high- and low-index particles and living cells

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For several years, researchers have relied on optical forces to trap and manipulate microscopic objects. An optical trap serves as a tool for grabbing and moving a microscopic object in a non-invasive manner. A key reason why optical means are favoured for particle manipulation is the fact that light can be fashioned into multiple trapping beams for parallel handling of a plurality of particles. Such parallel trapping functionality has the potential for revolutionising experimental approaches within biology, chemistry, colloidal science and fluidics on the microscopic scale.

We have recently reported advanced optical trapping with a method that equips the user with multiple dynamic beams to simultaneously trap and independently manipulate microscopic materials whose indices of refraction can either be higher or lower than that of the suspending medium.[1,2] This will allow researchers to work with materials of varied specifications like solid particles and air bubbles simultaneously.

In Figure 46 (a)-(c), we show simultaneous optical trapping and real-time interactive manipulation of a particle mixture of three polystyrene microbeads and three hollow glass microspheres in water (refractive index n = 1.33). High-index (polystyrene spheres; n = 1.57) and low-index (hollow glass spheres; $n \sim 1.2$) particles are trapped in the transverse plane by an array of confining optical potentials created by beams with top-hat and annular cross-sectional intensity profiles, respectively. By applying the so-called generalised phase contrast (GPC) method,[3-5] a wide variety of scalable intensity profiles can be created. The GPC method maps dynamic spatial light modulator patterns in a way that requires virtually no computational power, and allows arbitrarily profiled trapping beams.

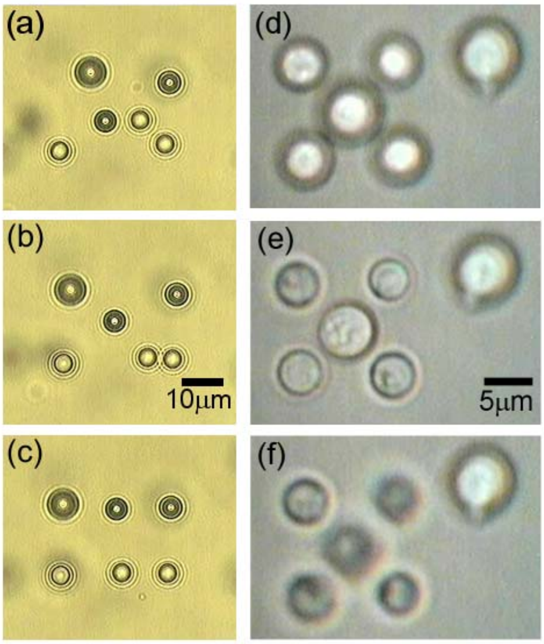

Figure 46. Optical manipulation of high- and low-index particles and viable yeast cells S. cerevisiae. The system is based on the generalised phase contrast method for high light-throughput synthesis of arbitrary intensity patterns that form multiple optical traps for dynamic and real-time manipulation of fluid-borne microscopic objects.

Aside from the ability to synthesise arbitrary trapping profiles, which provides independent transverse particle-position control, we have extended the system to enable simultaneous position control along the depth dimension.[6] To achieve this, we first transform the linearly polarised GPC-generated intensity pattern into an arbitrary elliptic polarisation state using a transmitting liquid-crystal device that acts as a variable waveplate. Then, the generally elliptic-polarised intensity pattern is passed through a polarising beam splitter to form two linearly polarised (orthogonal polarization) images of the intensity pattern. By optically relaying the two intensity images to the sample plane and having them transversely superimposed, an array of counterpropagating beam traps is formed. Figure 46 (d)-(f) shows the control of the axial positions of simultaneously trapped yeast cells in five pairs of counterpropagating beams. Axial position control is achieved by simply adjusting the relative strengths of the opposing beams, which is done losslessly by this polarisation-encoding scheme. The flexibility of our approach can also allow cells to be manipulated even within high-index liquid media. This is important for cell studies that involve various types of microbial solutions other than a host medium that is mainly composed of water.

We believe that the GPC-based optical micro-manipulation system could pave the way for numerous applications in the fields of bio-, materials and micro-technologies, including many technical applications that have been unrealizable until now.

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3.5.3 Micro-optical GPC-based cryptography

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While most common implementations of cryptographic techniques are performed via electronic or computer-based algorithms, cryptography that operates in the optical domain has proved to yield ciphered information in addition to extremely fast decryption via parallel optical processing. To date, most of the proposed optical cryptographic methods have been undertaken using classical macro-optical systems. Miniaturising the optical components will provide more realistic applications and will potentially enable direct interfacing to microelectronics-based devices. We have previously demonstrated miniaturising the generalized phase contrast (GPC) method[1-4] in a planar-integrated micro-optics (PO) platform.[5-7]

Implementing optical processes on a PO platform allows coupled light to undergo free-space propagation between the integrated micro-optical components. The GPC-PO device is therefore a particularly robust implementation that is not prone to position tolerances and alignment problems, which are major issues when using discrete and macro-optical components.

In the miniaturised set-up, the GPC-based visualisation of the decrypted pattern is achieved in a folded optical path configuration via the GPC-PO device shown in Figure 47. The micro-lenses of the 4f lens set-up and the PCF at the Fourier plane are integrated into a single optical flat. Multiple-phase level diffractive micro-optical elements are fabricated on the topside of a glass substrate using multi-mask lithography. The micro-lenses are reflection coated and fabricated using two binary lithographic steps that make up a 4-phase level diffractive optical element. The first micro-lens focuses the beam to the Fourier plane where the reflection-coated circular PCF is positioned to introduce a π-phase shift to the on-axis region of the focused light. The PCF is fabricated as a 7-microns diameter pit on the substrate. The reverse optical Fourier transform is performed in the succeeding half of the symmetric system.

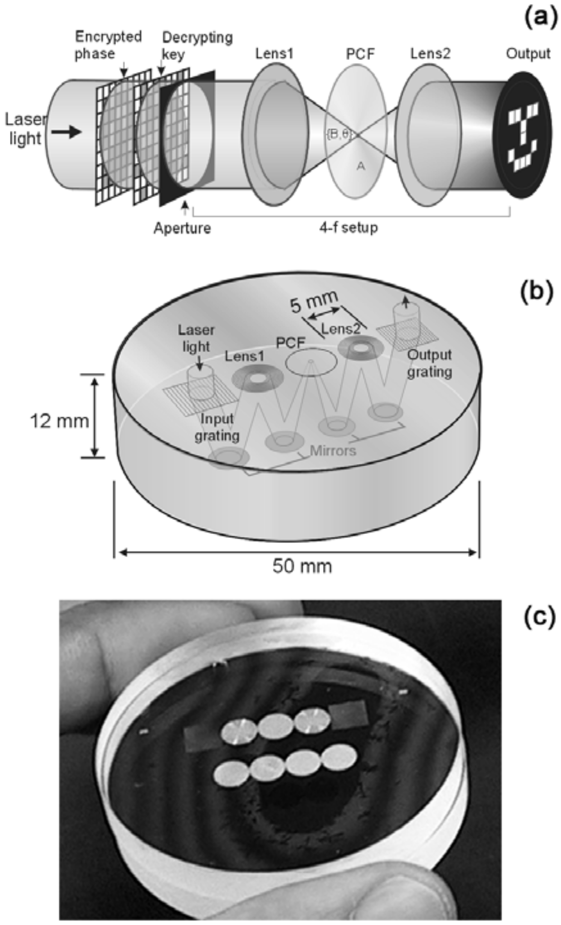

Figure 47. (a) Phase-only optical decryption using the generalized phase contrast (GPC) method. (b) Diagram and (c) photograph of the planar-integrated optical implementation of the GPC method.

We have carried out “proof-of-principle” experiments with the GPC-PO device shown in Figure 47c. The decrypting key information is encoded using a phase-only SLM that is illuminated from an expanded laser beam. The encrypted phase mask is fabricated on an optical flat where the phase-shifting pixels of 0 and π constitute a 17×9-pixel phase key where the size of each pixel is approximately 176 by 333 microns. In the current “proof-of-principle” experiment, an external macrooptical set-up is necessary to scale both the encrypted and the key patterns to the appropriate sizes for imaging using the GPC-PO device. The prospect, however, is to miniaturise the entire optical set-up into a fully integrated micro-optical system. Figure 48 shows the intended implementation of the whole optical setup in planar integrated optics using a two-stage 4-f lens set-up. An image of a phase-encrypted pattern is projected on the decrypting phase key pattern using the first 4-f lens set-up. An encrypted phase-only pattern recorded on a bankcard, a passport, a currency note, etc. can instantly be verified for authenticity by subjecting it to this planar integrated set-up. The phase-only key can be dynamically encoded on a compact, electronically controlled liquid crystal on silicon (LCOS) SLM. Non-mechanical alignment of the two-phase patterns can be achieved by an automated electronic scrolling of the pattern encoded on the LCOS-SLM. The decrypted phase data are then converted into an intensity pattern using the GPC method via the second 4-f filtering set-up. The intensity pattern at the output can subsequently be recorded using a detector array and can be transformed to another medium of transmission.

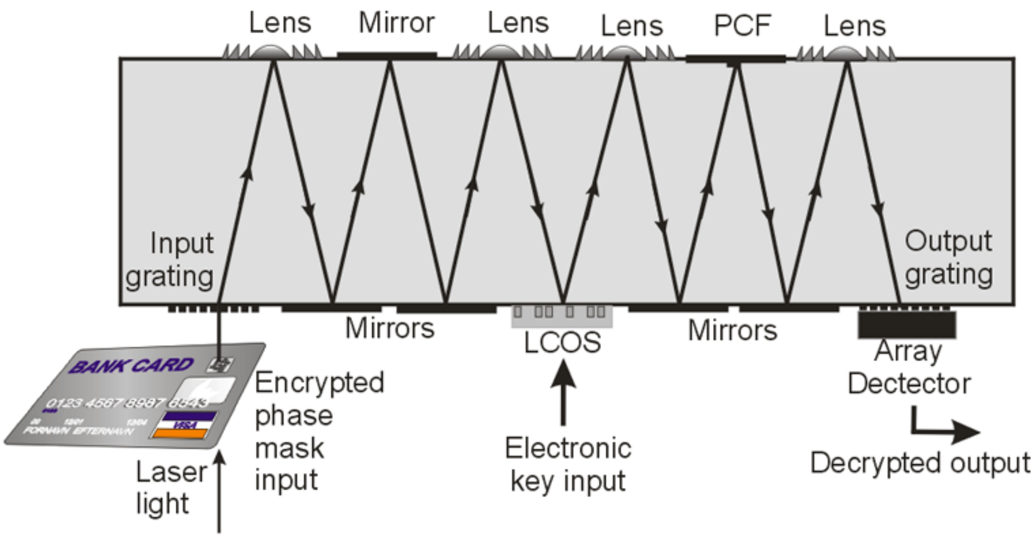

Figure 48. The proposed integration of the whole phase-only decrypting set-up using a two-stage 4-f lens planar optical system. The phase-encrypted pattern is read out from a credit card and the phase-only decrypting key is dynamically reconfigured and spatially aligned on an electronically addressed liquid crystal on silicon spatial light modulator.

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4. Plasma Physics and Technology

4.1 Introduction

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At the start of 2004, the research programme changed name from *Plasma and Fluid Dynamics* to *Plasma Physics and Technology.* As a follow-on from that, the department changed name to *Optics and Plasma Research Department.* This change of name reflects our commitment to concentrate and build on our core competence in plasma physics, spanning the field from the high temperature plasmas required for fusion energy to low temperature plasmas for a broad range of current and near-term environmental and industrial applications. The latter include cleaning of exhaust gases, sterilisation, material synthesis, and modification of surfaces for instance to improve adhesion.

A plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true of the transition from a gas to a plasma; in fact the plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. Just as solid state physics is involved in a broad range of applications, so it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at Risø, and gives us access to placing our experimental equipment on large fusion facilities at the Max-Planck Institute for Plasma Physics in Garching and at the Research Centre Jülich, both in Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area.* Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 4.1.1, and described in further detail in subsection 4.2 discussing turbulence and transport in fusion plasmas, and in subsection 4.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

Our relatively new activities in low temperature plasmas are introduced in subsection 4.1.2 These activities were initiated in 2003 with a project to reduce NOx emissions from gas power stations as reported in subsection 4.4. Activities in the fields of sterilisation, material synthesis and surface modifications are growing and described in subsection 4.4. The surface modification activities are pursued in collaboration with the Materials Research Department and the Danish Polymer Centre, both at Risø.

4.1.1 Fusion plasma physics

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Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and visa versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere × seconds and is currently one atmosphere × seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 4.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER, which has been designed and is currently being negotiated between the participants, i.e. Europe, Japan, Russia, USA, China and Korea. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. It is in fact also one of our main research topics in fusion as reported in subsection 4.3.

The fields of turbulence, transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in edge transport barriers; most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the TEXTOR tokamak at the Research Centre Jülich and at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, both in Germany.

Our aim is not only to understand the dynamics, but also to identify external actuators with which the turbulence and transport can be controlled. The first demonstrations of edge turbulence control with arrays of electrostatic probes have been made in a linear device in collaboration with other associations. Selective ejection of core fast ions by sawteeth, which in turn can be manipulated by a localised heating and current drive, was found in fast ion CTS data obtained at TEXTOR in collaboration with TEC[1] and MIT, USA.

1. TEC: the Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, Netherlands; and Association EURATOM-ERM/KMS, Belgium.

4.1.2 Low temperature plasma technology

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Unlike high temperature plasmas encountered in fusion research, low temperature plasmas are mostly partially ionised. That is, they are mixtures of electrons, ions and neutrals that can be atoms, radicals and molecules in various states of excitation. The dynamics of low temperature plasmas thus include a rich field of plasma chemistry. Low-temperature plasmas can be generated by exciting and ionising gas mistures. Excitation from fluid or solid mixtures is also possible. Excitation can be achieved by a wide variety of means ranging from lasers over microwaves and radio waves to pulsed and low frequency electromagnetic or DC excitation. The method of excitation, the gas mixture, the pressure and ambient conditions all influence the state of the plasma and hence its properties. Low temperature plasmas can be highly aggressive and used for cutting or etching solids, or so gentle that they can be applied directly to plastics or human skin. To meet the demands of a specific application it is often essential to design the state of the plasma carefully. Here the energy distributions of electrons, ions and neutrals, which can be quite different, may be important, just as the distribution of energy states of neutrals and concentrations of radicals can. Anisotropies, induced for instance by magnetic fields, and inhomogeneities can be designed and be essential for certain applications, just as temporal variations in the plasma state can be. Diagnosing and modelling the plasma state is crucial in designing the plasma for a specific application. Diagnostic techniques include emission and absorption spectroscopy, interferometry and scattering, and material probes. For industrial exploitation there is considerable process and financial advantage to operation at atmospheric pressure. Scientific investigation and development of such plasmas has expanded dramatically in recent years, in part driven by needs of industry. Our new activities in low temperature plasmas for environmental and industrial applications, described in subsection 4.4, thus also emphasise atmospheric pressure plasmas, though not to the exclusion of low pressure plasmas.

4.2 Turbulence and transport in fusion plasmas

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The transport of heat and particles across the confining magnetic field of fusion plasmas is one of the most important and interesting, but also most difficult areas of contemporary fusion research. It is well established that the "anomalous" transport component mediated by low frequency turbulence is far larger than the classical collisional transport. It is thus of utmost importance to achieve a detailed understanding of this transport and the underlying turbulence for the design of an economically viable fusion reactor based on magnetic confinement schemes. In spite of dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still very sparse and any predictive capacity is at best rudimentary. Even very fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

We have mainly focussed our activities in plasma turbulence and transport on topics related to edge turbulence. It is found that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region. Our investigations are based on numerical solutions of first-principle models, and we aim at benchmarking results and performance with other codes and also with experimental observations when available.

Our investigations have comprised direct numerical simulations of the transport of impurities in the edge plasma region (see subsection 4.2.1), where we found strong asymmetric transport features with dominating pinch convection on the low-field side and an anti-pinch, i.e. outward convection, at the high-field side. We have furthermore investigated the influence of finite inertia effects on the mixing and transport of impurities (see subsection 4.2.2), where we observed a local clustering of the impurity density in vortical structures and an additional pinch effect; both of these features were found to scale with the mass to charge ratio of the impurities. The up-gradient transport and the profile resilience were examined by using a probabilistic transport model with two different particle step lengths depending on the local value of the gradient (see subsection 4.2.3). This serves as a phenomenological model for the interplay between classical transport and anomalous transport setting in when the gradient exceeds a critical value. Indeed profile peaking and resilience could be obtained for off-axis fuelling.

In subsections 4.2.4, 4.2.5 and 4.2.6 we consider the bursting and intermittency in the fluxes of particles and heat in the edge and scrape-off-layer (SOL) of a toroidal plasma. The key mechanism here is the nonlinear energy exchange between global poloidal flows and small-scale turbulent fluctuations. In subsections 4.2.4 and 4.2.5 we have employed the energy conserving global model for interchange dynamics at the transition from the edge to the SOL. Results from this model are directly compared with recent experimental observations and reproduce in detail the observations of plasma blobs propagating far out into the SOL (see subsection 4.2.4). These propagating blobs are responsible for strongly intermittent bursts of hot plasma, which pose a serious problem to plasma facing components in next generation devices like ITER. Comparison of the statistical properties of ion and electron energy fluxes to the divertor plates is envisaged as a next step.

The self-consistent generation of large-scale flows by rectification of the small-scale turbulent fluctuations is receiving increasing interest in recent years. These flows can set up transport barriers and are assumed to play a crucial role in the transition from the low confinement to the high confinement regime (LH-transition) and also for internal transport barriers. However, the exact mechanisms for flow generation have not been quantitatively assessed yet. We have investigated the generic flow generation from turbulence in drift-Alfvén turbulence in subsection 4.2.7. By covering a broad range of parameters we have revealed the relative importance of the different sources and sinks for the flows. The Reynolds stress is always acting as a source for the flow, but for increasing plasma beta the so-called Maxwell stress, which is due to magnetic field fluctuation, comes into play. This is a sink for the flow energy and eventually counteracts the Reynolds stress limiting flow generation. However, a third effect arising from the geodesic part of the magnetic field curvature and being a sink for low beta values changes sign for higher beta values and in this regime becomes the main drive for the flows. These results indicate that it may be misleading to project the strength of large-scale flow mediated transport barriers from low beta plasmas to high beta plasmas in, e.g., ITER.

Finally, in subsection 4.2.8, we show the results of a linear analysis of the drift-wave mode structure in a collisional plasma. Predictions from linear theory taking proper account of the spatial dependence of collisionality are in detailed agreement with experimental observations, paving the way for a detailed comparison between turbulent experimental states and fully non-local 3D simulations.

4.2.1 Impurities in tokamak edge turbulence

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Transport of impurities through the edge region of a toroidal confinement device is still poorly understood. Modelling of experimental results shows that we have to invoke anomalous effects to explain the observed impurity concentrations. These effects include anomalous diffusion coefficients as well as anomalous pinch velocities. We here investigate the transport of ideal, in the sense of massless, passive particles under the action of electromagnetic drift Alfvén turbulence.

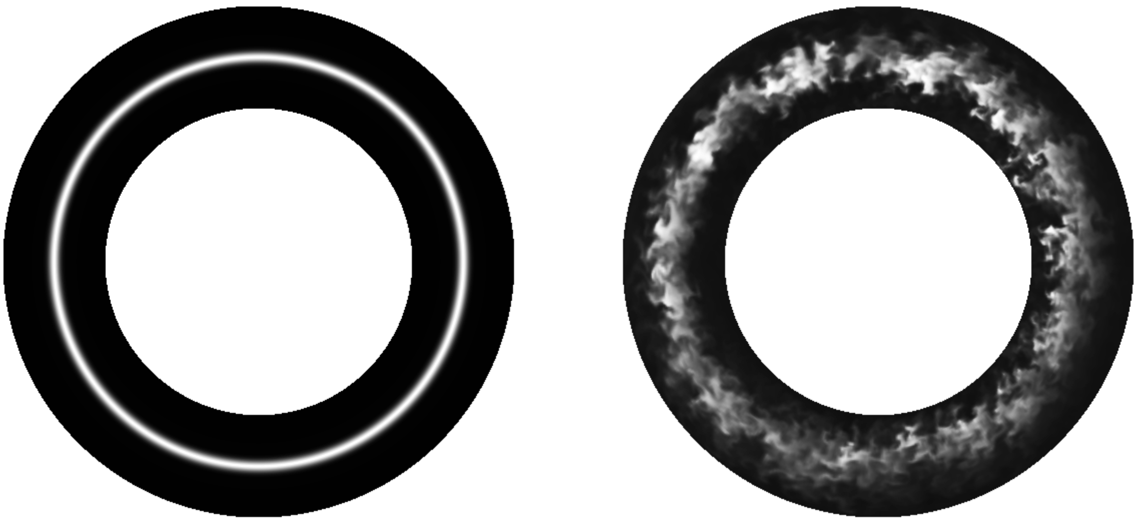

Figure 49. Poloidal cross section showing initial impurity density and impurity density after some turbulent mixing.

We recover the curvature-related particle pinch for the impurities, which is predicted within the concept of turbulent equipartition. The net inward pinch velocity of the impurities then results from a combination of the curvature pinch (which is inward on the low-field side and outward on the high-field side) with the ballooning properties of the turbulence.

Using turbulent equipartition, an approximate relationship between anomalous diffusion and anomalous pinch can be found, a relationship that is confirmed by the numerical simulations.

1. V. Naulin, Impurity and trace tritium transport in tokamak edge turbulence, Physical Review E **71**, 015402, (2005).

4.2.2 Anomalous diffusion, clustering and pinch of impurities in plasma edge turbulence

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It is well established that turbulence is the dominant transport mechanism for particles and heat in the edge region of magnetised plasmas. Turbulence moreover has a strong influence on the transport of impurities in this region. Pinching of impurities, i.e. a fast convective inward transport, is generally observed in experimental investigations in addition to the turbulent diffusive spreading. This has also been the case for the trace-tritium transport investigations in JET.[1]

We have investigated the turbulent transport of impurities in plasma edge turbulence employing the two-dimensional Hasegawa-Wakatani model for resistive drift-wave turbulence. The impurity evolution is modelled by tracing a passive scalar field in the self-consistently developed turbulence obtained from the solution of the Hasegawa-Wakatani equations. Various features of the impurity transport are examined by means of numerical simulations using a novel code that applies semi-Lagrangian pseudo-spectral schemes. In particular, we have investigated the influence of finite inertia in the advection of the impurities. This influence is accounted for in the polarisation drift and is becoming increasingly important for rising mass-charge ratio of the impurity species. In this case the velocity field experienced by the impurity field is compressible, which will lead to local accumulations of the impurities and which will also be instrumental in the pinch effect. Correspondingly we found that the density granulation of the impurities is correlated with the vorticity field, i.e. impurities cluster in vortices of positive vorticity, while they are expelled from vortices of negative vorticity as illustrated in Figure 50. In addition, we observed a radial pinching of the impurities. Both the clustering effect and the pinching are increasing with rising mass-charge ratio of the impurities.

1. K.D. Zastrow, Nucl. Fusion **39**, 1891 (1999).

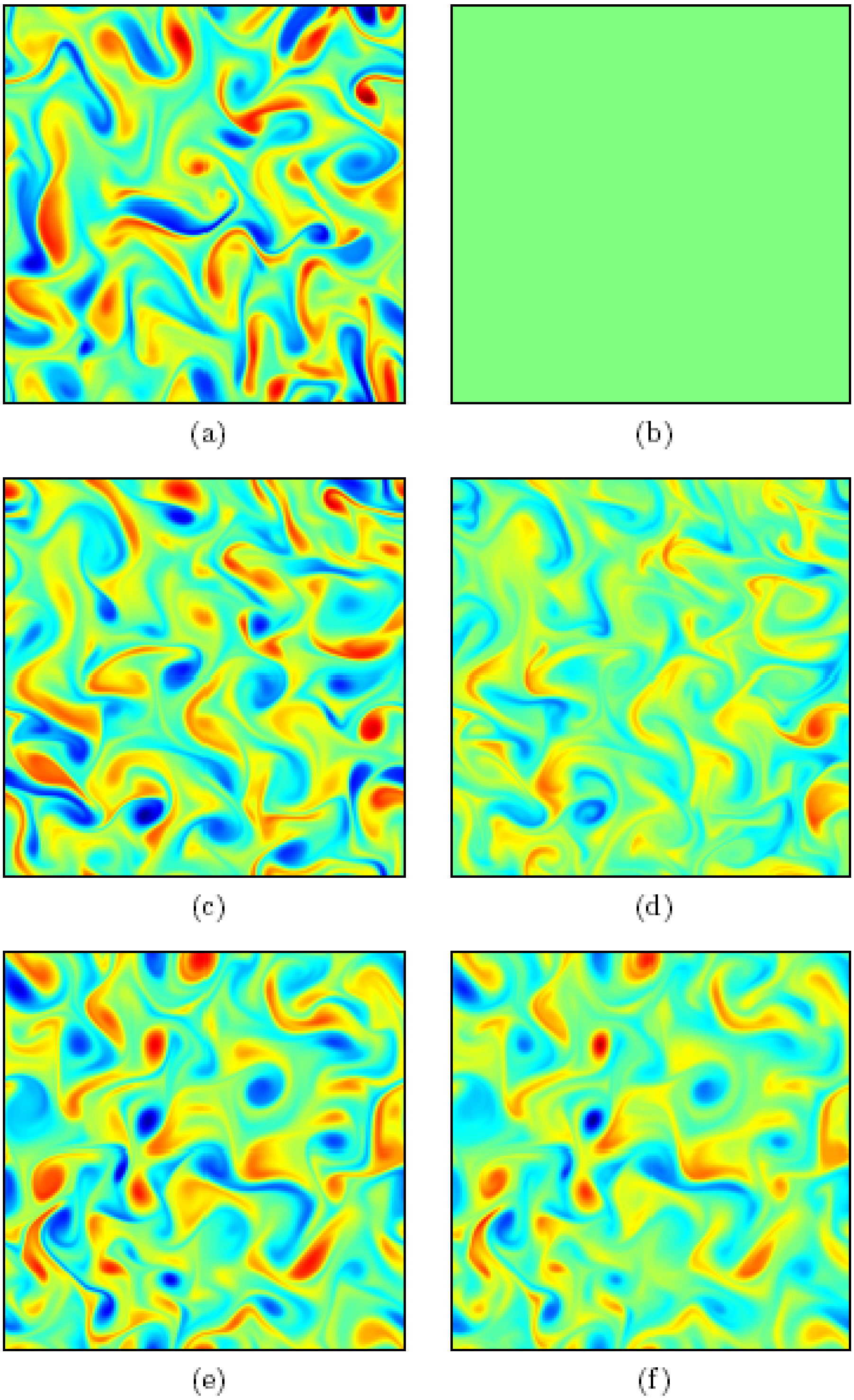

Figure 50. Fig. 1. Time evolution of the vorticity field (left panel) and the perturbation of an initially (t = 0) uniformly distributed impurity density (right panel). (a,b) t = 0, (c,d) t = 5 and (e,f) t = 50. Blue represents negative values and red represents positive values.

4.2.3 On the up-gradient transport in a two-step diffusion model

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The cross-field transport of particles and heat in magnetically confined hot plasmas is a complex and only partially understood issue. It is composed of several elements including classical and neo-classical collisional diffusion and anomalous turbulent transport. Several "strange" features characterise the transport. Examples are up-gradient transport (i.e. transport in the direction of the gradient), profile resilience or consistency (i.e. the existence of stiff profiles that are only weakly dependent of the fuelling), rapid transport phenomena (i.e. perturbative transport events that are significantly faster than the diffusive transport derived from the background gradients). These features cannot consistently be explained by simple "Fickian" diffusion in which the transport is assumed to be governed by diffusivities.

Recently, van Milligen *et al.*[1] have proposed a probabilistic model for the description of the transport and the evolution of the density profile in a plasma with external sources. The model is based on an explicit time- and space-dependent particle step probability distribution function, PDF. This PDF is assumed to depend on the local density gradient. When the gradient is below a critical value, the PDF is a Gaussian distribution with a standard deviation ("step size") σ_2; this will correspond to a normal diffusive process and mimics the collisional diffusion. However, when the gradient is larger than a critical value, the PDF is argued to be of the Lévy type, i.e. with no characteristic length scale. This shall mimic the anomalous transport mediated by turbulence and shall signal that there are long-range correlations. Van Milligen *et al.*[1] have solved this model for many different situations with various source distributions and have found that it reproduces several of the "strange" features mentioned above. It was strongly emphasised that the Lévy-type particle step PDF is essential for the observed characteristics.

We have re-examined the model of van Milligen *et al.* to investigate the sensitivity of the results on the assumed particle step PDFs. In particular, we have solved the model for the case where also the PDF for supercritical gradients is a Gaussian with a "step size" $\sigma_1 > \sigma_2$. We have basically reproduced the transport features observed by van Milligen *et al.* In Figure 51 we show the typical density profile when the fuelling is off-axis for the case of two Gaussian particle step PDFs, with $\sigma_1 = 0.08$ and $\sigma_2 = 0.02$. The density profile is clearly peaked in the centre and is very similar to the profile obtained for the case when the particle step PDF for supercritical gradients is a Cauchy (Lévy) distribution as used in ref. 1. We should note that we obtained a similar profile using asymmetric off-axis fuelling, i.e. only one source displaced from the centre. In Figure 52 we demonstrate the profile consistency by plotting the central density, $n(x = 0.5)$, for different source strengths, S_0 and various particle step PDFs. It is observed that $n(x = 0.5)$ is roughly constant over a broad range of source strengths S_0, for the case of a Gaussian and Cauchy PDF as well as for two Gaussians when $\sigma_1 > 2\text{-}3\ \sigma_2$. This is a signature of profile consistency. We have thus demonstrated that the essential feature for obtaining profile peaking and consistency in transport models is the existence of a step size PDF regulated by a critical gradient. The effective step size above the critical gradient, in the anomalous channel, must be sufficiently larger than the step size in the classical channel. However, it is not necessary to have a Lévy type PDF for the anomalous transport channel.

1. B.Ph. van Milligen, B.A. Carreras, and R. Sánchez, Phys. Plasmas **11**, 3787 (2004); ibid **11**, 2272 (2004).

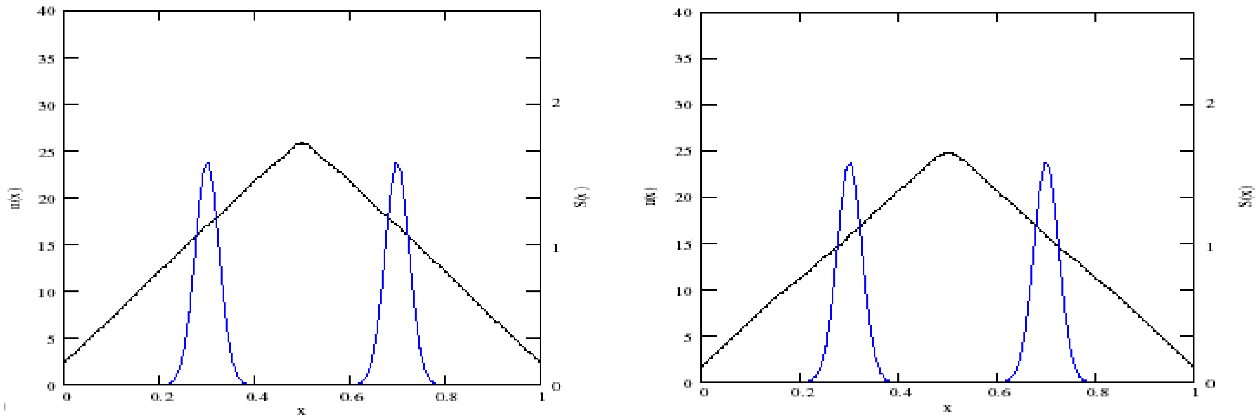

Figure 51. The density profile with symmetric off-axis fuelling. The sources are shown by the blue curves ($S_0 = 0.2$), for different transport step size PDFs. (a) Two Gaussian distributions with the step sizes: $\sigma_1 = 0.08$ and $\sigma_2 = 0.02$. (b) A Cauchy and a Gaussian distribution as used by van Milligen et al.[1]

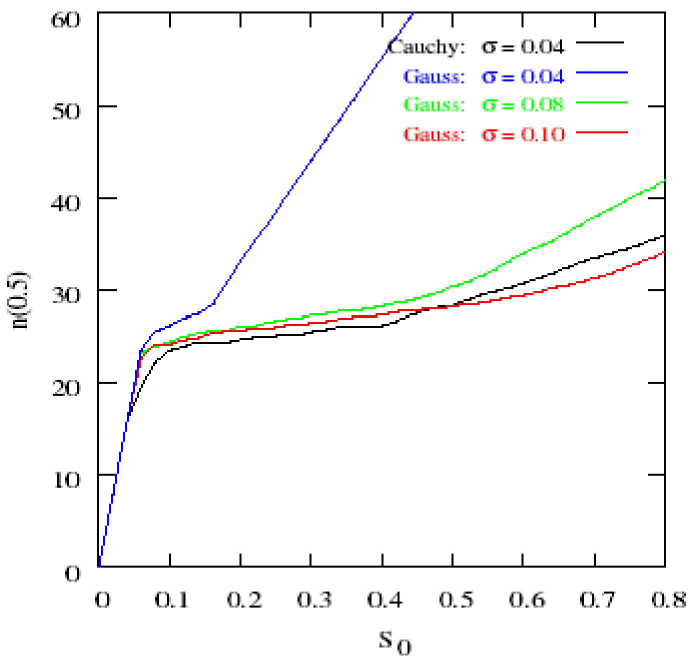

Figure 52. Profile "stiffness" shown by the dependence of the central density on the source strength S_0, for the cases where the anomalous transport channel is characterised by a Cauchy distribution and the cases where it is a Gaussian with the values of σ_1 shown in the caption.

4.2.4 Simulations of blob propagation in edge and scrape-off layer of toroidal plasmas

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Numerical fluid simulations of interchange turbulence for geometry and parameters relevant for the boundary layer of magnetic confinement devices have shown to result in intermittent transport qualitatively similar to many recent experimental measurements. The two-dimensional simulation domain features a forcing region with spatially localised sources of particle and heat outside which losses due to motion along open magnetic field lines dominate, corresponding to the edge and the scrape-off layer (SOL), respectively.[1,2] The results obtained from the simulations are compared with experimental observations at the Alcator C-Mod.

In turbulent states we observe intermittent eruptions of hot plasma from the edge region, propagating radially far into the SOL in the form of field-aligned filaments, or blobs. Here they are dissipated due to transport along open magnetic field lines. In between these quasi-periodic bursts, the flow settles into a self-generated shear flow stopping the radial transport almost completely. The radial propagation velocity of the blobs may reach one tenth of the sound speed, in excellent agreement with experimental measurements at Alcator C-mod.

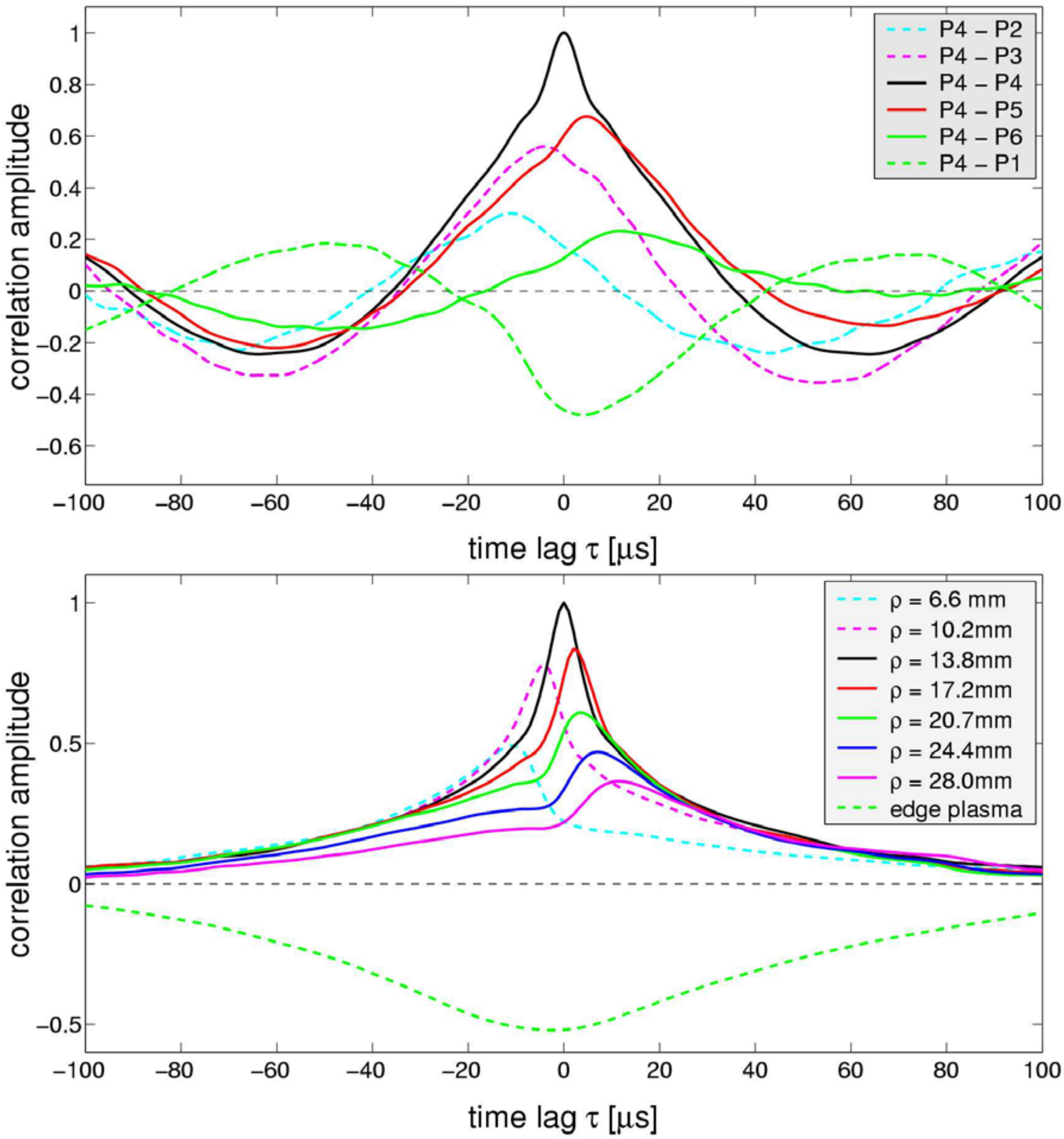

Figure 53. Top: The correlation of the density signal between P4 with the other probes. The seven probes are distributed equidistantly in the radial direction with P1 being located in the edge region and P2 at the LCFS. Bottom: the corresponding curves for the Alcator experiment.

The statistics of single-point recordings obtained at different radial positions, Pi, from the simulations have been compared with data from Alcator C-mod. An example of this comparison is shown in Figure 53. The two frames display the correlation of the density signal between a probe located well into the SOL, P4 in the simulation, with the signal from the other probes. In both cases we observed a clear indication of an outward moving structure and we observe an anti-correlation at time = 0 for the probe located in the edge region.

1. O.E. Garcia, V. Naulin, A.H. Nielsen and J. Juul Rasmussen, "Computations of Intermittent Transport in Scrape-Off Layer Plasmas", Phys. Rev. Lett. **92**, 16 (2004).
2. O.E. Garcia, V. Naulin, A.H. Nielsen and J. Juul Rasmussen, "Turbulence and intermittent transport at the boundary of magnetized plasmas", submitted to Phys. Plasmas (2005).

4.2.5 Turbulence and intermittent transport at the boundary of magnetised plasmas

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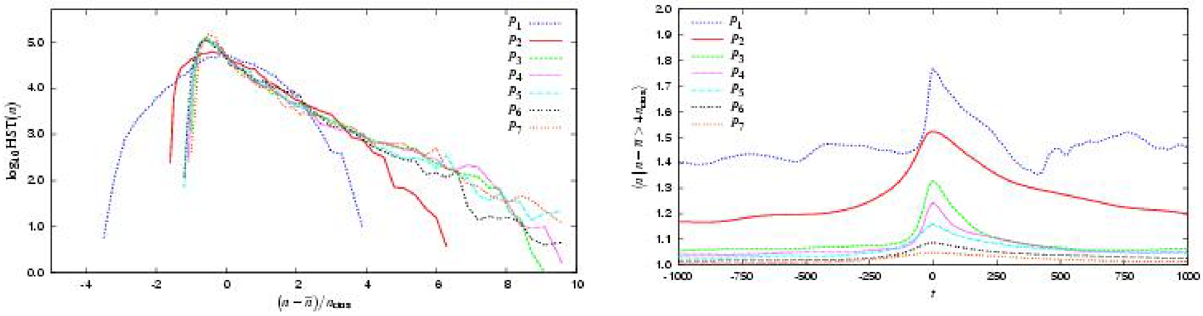
A three-field fluid model for plasma density, electron temperature and fluid vorticity has been derived in order to describe the edge and scrape-off layer region of a magnetised plasma.[1,2] The model is based on interchange modes due to a non-uniform magnetic field, neglecting small-scale drift wave dynamics as well as magnetic shear. However, the fully non-linear flow compression terms are maintained in order to describe the order unity perturbation of the dependent variables that is observed experimentally.

Numerical simulations for geometry and parameters relevant to the boundary region of magnetic confinement devices are shown to result in intermittent transport qualitatively similar to many recent experimental measurements. The two-dimensional simulation domain features a forcing region with spatially localised sources of particles and heat outside which losses due to motion along open magnetic field lines dominate, corresponding to the edge region and the scrape-off layer, respectively.

In turbulent states we observe intermittent eruptions of hot plasma from the edge region, propagating radially far into the scrape-off layer in the form of field-aligned filaments, or blobs. This results in positively skewed and flattened single-point probability distribution functions of particle density and temperature, reflecting the frequent appearance of large positive fluctuations (Figure 54a). Moreover, the conditional fluctuation waveforms and transport statistics are in good agreement with those derived from experimental measurements (Figure 54b).

Associated with the turbulence bursts are relaxation oscillations in the particle and heat confinement as well as the kinetic energy of the poloidal flows. The formation of blob structures is thus related to profile variations that may be triggered in a quasi-periodic manner by a global dynamical regulation due to sheared flows. These results support the idea that any turbulence propagating into the region of open magnetic field lines leads to radial propagation in the form of blobs, thereby extending the present results to the propagation of edge localised modes.

1. O. E. Garcia, V. Naulin, A. H. Nielsen, and J. Juul Rasmussen, Phys. Rev. Lett. **92**, (2004).
2. O. E. Garcia, V. Naulin, A. H. Nielsen, and J. Juul Rasmussen, "Turbulence and intermittent transport at the boundary of magnetized plasmas", submitted to Physics of Plasmas 2005.



a) b)

Figure 54. a) Single-point probability distribution functions of the particle density, reflecting the frequent appearance of large positive fluctuations. b) Conditional fluctuation waveforms of the density.

4.2.6 Two-dimensional thermal convection in fluids and magnetised plasmas

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A paradigmatic two-field fluid model describing convective motions in fluids as well as magnetised plasmas has been investigated analytically and numerically. In the fluid case, the baroclinic generation of vorticity is the source of convection, while magnetic guiding centre drifts in non-uniformly magnetised plasmas act to drive similar motions known as interchange, resistive-g and ballooning modes.[1-3]

The close relationship between these mechanisms for vorticity generation is exploited to give a new perspective for the onset of convective motions and sheared poloidal flows in magnetised plasmas. This also contradicts the general view of turbulent transport as essentially “collisionless”.

Non-linear numerical simulations saturating in stationary convective states reveal the process of laminar scalar gradient expulsion, leading to the formation plumes in the pressure field as well as vorticity sheets. These dissipative structures have been demonstrated to result in temperature profile consistency and transport scaling at large Rayleigh numbers.[2,3]

In the case of self-sustained sheared azimuthal flows, the turbulence has a bursty nature associated with relaxation oscillations in the kinetic energy of the mean azimuthal flows. This leads to a state of large-scale intermittency manifested by exponential tails in the single-point probability distribution functions of the dependent variables. The global bursting may be interpreted in terms of a predator-prey regulation from the point of view of energetics.[1,2]

1. O. E. Garcia and N. H. Bian, Phys. Rev. E **68**, 047301 (2003).
2. O. E. Garcia, V. Naulin, A. H. Nielsen, J. Juul Rasmussen, and N. H. Bian, “Two-dimensional thermal convection in fluids and magnetized plasmas"” submitted to Physica Scripta 2005.
3. N. H. Bian and O. E. Garcia, Phys. Plasmas **12**, issue 4, to appear.

4.2.7 Shear flow generation and energetics in electromagnetic turbulence

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The self-consistent generation of large-scale flows by the rectification of small-scale turbulent fluctuations in magnetically confined plasmas has received strong interest during the last couple of decades. These flows may regulate the turbulence by suppressing the small-scale structures and set up transport barriers. It is generally believed that the sheared flows are instrumental in the LH transition now routinely observed in tokamaks and stellerators.

In electrostatic turbulence the Reynold stress (Re) is the source of interaction between large-scale flows and small-scale turbulence. This has been verified both in recent experiments[1] and in several numerical simulations of electrostatic turbulence. Here a strong correlation between the generations of sheared zonal flows and transport reduction is moreover clearly revealed.

In electromagnetic turbulence, which is important for finite beta plasmas as in, e.g., JET and ITER, an additional source of flow generation must be taken into account, the so-called Maxwell stress (Ma). In tokamak geometries the geodesic curvature effects, the so-called geodesic acoustic modes (GAM), will also interact with the flows in the system.

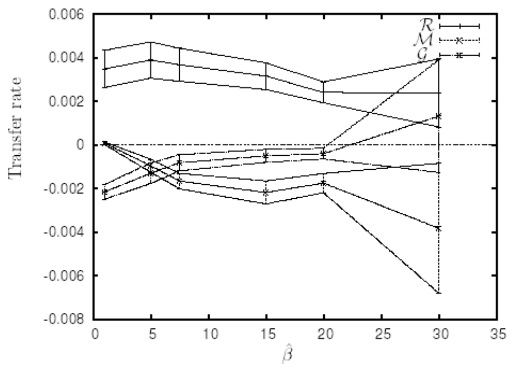

Figure 55. Dependence of the flow energy transfer rates on the scaled plasma beta.

We have examined the zonal flow generation in electromagnetic turbulence in the edge of tokamak plasmas by means of the Risø TYR code[2] governing the evolution of drift Alfvén turbulence in a 3D flux tube geometry. Covering a broad range of parameters we have revealed the relative importance of the different driving sources and sinks (Re, Ma, GAMs) for the self-consistent generation of the flows by quantifying the energy transfer into the flows due to each of these effects.

The main results have been summarised in Figure 55, where we depict the transfer rates due to three different sources/sinks. The Reynolds stress provides a drive for the flows while the electromagnetic Maxwell stress is nearly always a sink for the flow energy. In the limit high beta limit, where electromagnetic effects and Alfvén dynamics are particularly important, the Maxwell stress is found to cancel the Reynolds stress to a high degree. The GAMs, related to equilibrium pressure profile modifications due to poloidally asymmetric transport, are found to act as sinks as well as driving terms, depending on the parameter regime. For high beta cases, the GAMs are the main drive of the flow. This is also reflected in the frequency dependence of the flow, having a peak at the GAM frequency in that regime as shown in Figure 56.

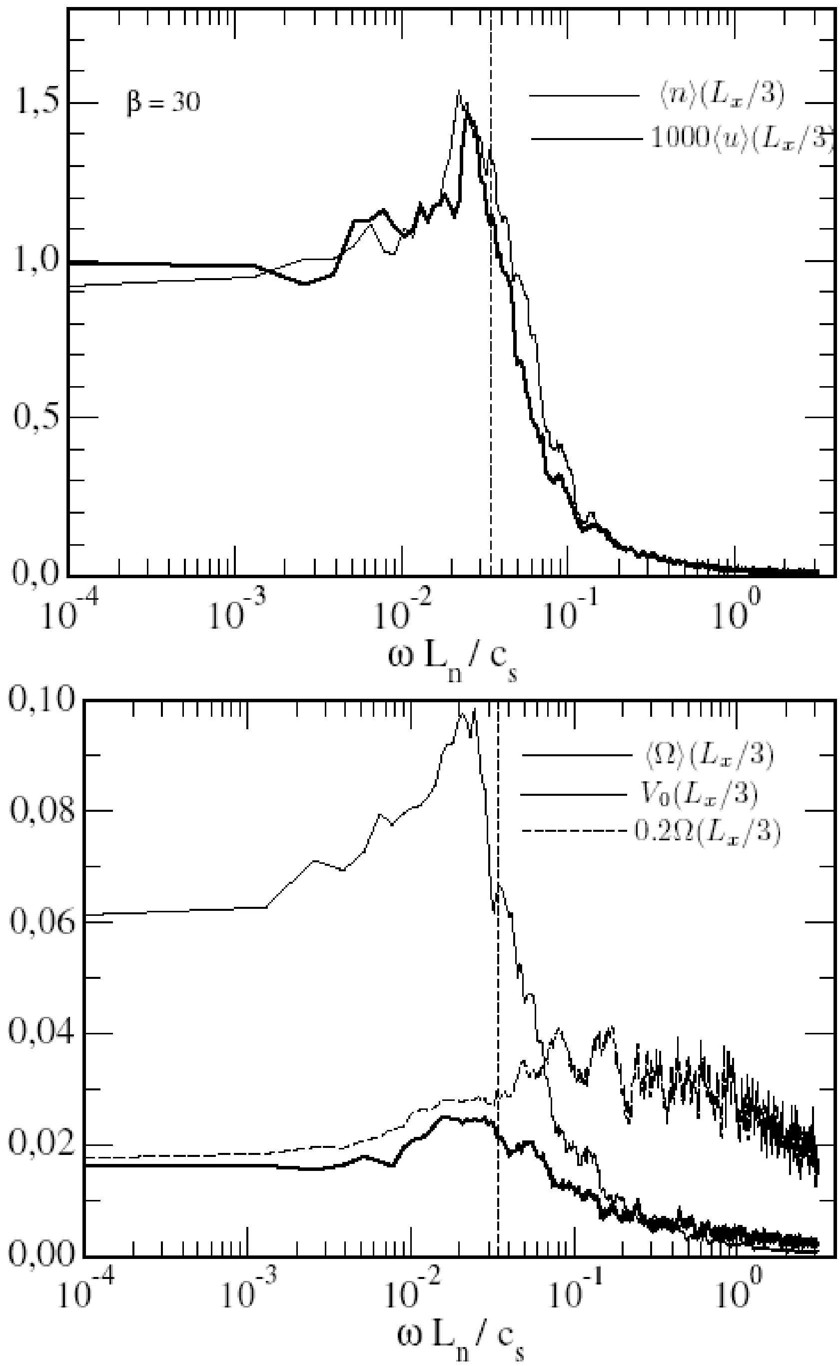

Figure 56. Frequency spectra of the quantities associated with the GAM oscillation (top) and zonal flows (bottom) for the high beta case. The vertical line shows the GAM frequency.

1. C. Hidalgo et al, Phys. Rev. Lett. **83**, 2203 (1999); Plasma Phys. Contr. Fusion **42**, Supl. 5A, A153 (2000).
2. V. Naulin, Phys. Plasmas, **10,** 4016 (2003).

4.2.8 Spatial mode structures of electrostatic drift waves in a collisional cylindrical helicon plasma

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In a cylindrical helicon plasma, mode structures of coherent drift waves are studied in the poloidal plane, the plane perpendicular to the ambient magnetic field. The mode structures rotate at a constant angular velocity in the direction of the electron diamagnetic drift and show significant radial bending. The experimental observations, see Figure 57, have been compared with numerical solutions of a linear non-local cylindrical model for drift waves,[1] see Figure 58. In the numerical model, a transition to bended mode structures is found if the plasma collisionality is increased. This finding proves that the experimentally observed bended mode structures are the result of high electron collisionality.[2]

1. Ellis et al., Plasma Phys. **22**, 113, (1980).
2. Christiane Schröder, Olaf Grulke, Thomas Klinger and Volker Naulin, Phys. Plasmas **11**, 4249, (2004).

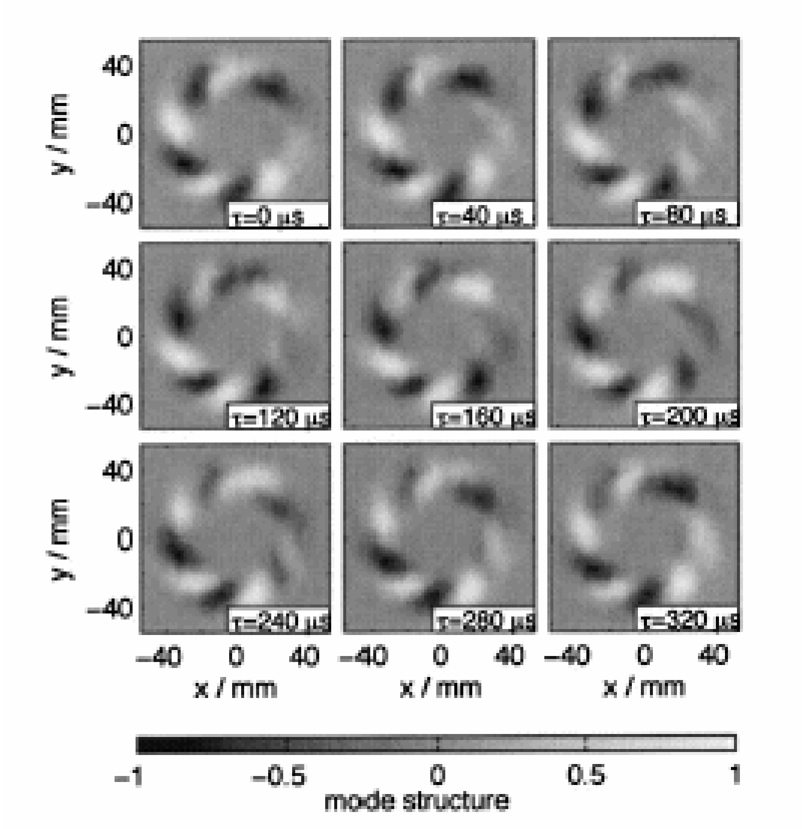

Figure 57. Poloidal mode structure obtained from the experiment.

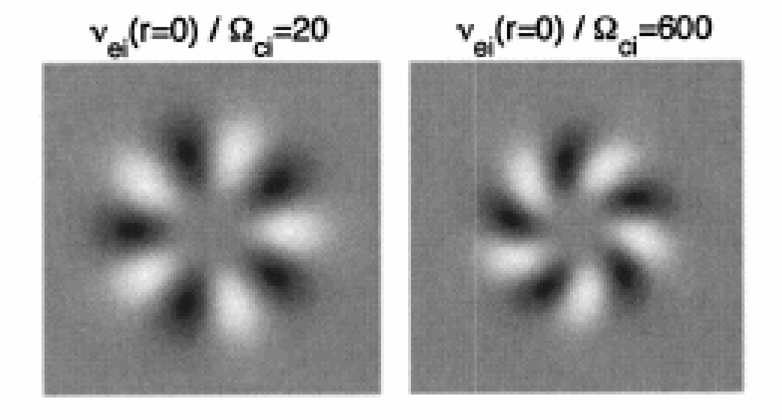

Figure 58. Poloidal mode structures obtained from the numerical model for two values of collisionality. Gaussian profiles are assumed for plasma density and Coulomb collisions, whereas the given value is the peak value.

4.3 Millimetre waves used for diagnosing fast ions in fusion plasmas

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Millimetre waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimetre scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to Megawatt range, CW. These technologies, widely used in fusion research, and in many cases specifically developed for fusion research, are now being considered for a broader range of commercial applications, including new GigaBit wireless Internet highways and wide area networks which avoid expensive trenching of optical fibres.

In the world of fusion, the millimetre waves are used extensively both as a diagnostic tool and as an actuator for manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimetre waves, like laser light, can be projected in narrow focused beams and, unlike laser light, the millimetre waves can interact strongly with the plasma.

At Risø we develop and exploit millimetre wave diagnostics for measuring the velocity distribution of the most energetic ions in fusion plasmas. The measurements are resolved in space on the centimetre scale and in time on the millisecond scale.

The most energetic (or fast) ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence in the plasma, and degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy, and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to tackle by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS).

The group has recently developed fast ion CTS diagnostics for the TEXTOR and ASDEX-Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. Further details of this work are given in subsections 4.3.1 and 4.3.2.

Testing and commissioning of the ASDEX CTS system was completed in 2004. The first CTS measurements are awaiting installation of the new step tunable gyrotron. The CTS system for TEXTOR has been under reconstruction at Risø and was installed at TEXTOR in August. Testing, commissioning and the first ECE measurements were performed later. These projects are conducted in collaboration with MIT, the Max-Planck Institute for Plasma Physics in Garching and the TEC[1] consortium.

A feasibility study of measuring the fast ion phase space distribution in ITER by CTS and a conceptual design including a cost estimate for a measuring system was completed in 2003. The study revealed that a CTS system based on a 60 GHz probe has the highest diagnostic potential, and is the only system expected to be capable of meeting all the ITER fast ion measurement requirements with existing or near term technology. A new contract for a detailed integrated design was obtained at the end of 2004. The main purpose is to develop a design to the level allowing detailed costing and detailed design specifications of in-vessel equipment layout and subsystems for a 60 GHz CTS measuring system. Especially, the antenna system on the high field side presents problems due to limited space between and behind blanket modules. A numerical model, set up in order to study possible options, is described in subsections 4.3.7.

1. TEC: the Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

4.3.1 Collective Thomson scattering diagnostic at ASDEX Upgrade

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The CTS diagnostic was installed at ASDEX Upgrade at the end of 2003. The system will eventually use the new ECRH system, in particular the new dual frequency gyrotron (105 GHz, 1MW, 10 sec pulse length) and the transmission lines. In 2004 the last phase of the hardware installation of the CTS system was completed. Installation of various components included new adjustable legs mounted under the receiver, the pin-switch control card that was installed and tested, and the motion of the movable mirror controller. With the help of the IPP ECRH technicians, the alignment of the quasi-optical transmission line was done using a laser. To improve the alignment in the millimetre range, a localised cold source and chopper techniques was applied whereby signals were partly measured by using one of the 1 GHz channels in the receiver and partly analysed by the LabView lock-in program. The trigger signals to the data acquisition system were incorporated with the CTS acquisition system and tested. The first ECE measurements of an ASDEX-Upgrade plasma were made. The central temperature was about 4keV. Preliminary studies comparing data from radiometry from electron cyclotron emission diagnostic have shown transmission losses larger than predicted. The most likely cause is the alignment of the CTS mirrors in the MOU box.

Figure 59. The Risø microwave receiver with the microwave horn pointing in to the hole in the MOU box.

4.3.2 Installation and commissioning of the upgraded fast ion collective Thomson scattering diagnostic at TEXTOR

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During 2004, the major upgrade to the fast ion collective Thomson scattering (CTS) diagnostic at TEXTOR (Institut für Plasmaphysik, Jülich, Germany) became ready for installation after two years of design, construction and tests at Risø. The main constituents of the upgrade are a new quasi-optical transmission line, a new data acquisition system and an upgrade to the receiver electronics. The need for the upgrade appeared by the end of the 2000 campaign of the pilot version of the CTS system at TEXTOR. During the campaign the system was operational and obtained many useful data using a 100 kW, 0.2 s, 110 GHz gyrotron, courtesy of FOM, Holland. However, due to the location of the CTS electronics close to the tokamak and configuration changes on TEXTOR itself, noise became an increasing problem.

The details of the upgrades are the following:

(a) The receiver antenna and transmission line: a new quasi-optical transmission line has been designed and constructed. It consists of a universal polarizer and seven quasi-optical mirrors including a steerable (+/- 30° horizontal and +/- 15° vertical) plasma facing mirror.

The new transmission line allows the CTS electronics to be located on the wall of the bunker far from the tokamak (3-4 m).

(b) The electronics: The upgrade to the electronics was mainly to replace noisy components and to split the high frequency band from the centre frequency band in order to reduce the influence of possible stray light on the high frequency channels. The receiver electronics feeds 42 filters covering a frequency range that enables ion velocity distribution measurements corresponding to an ion deuterium energy range of ~ 0.5 to 200 keV. (See Section 2.2.4 *Electronics for the CTS diagnostics at ASDEX Upgrade and TEXTOR* in the annual report of 2003 for more details of the electronics in the receiver).

(c) The data acquisition system: A new National Instruments data acquisition system with 48 channels at 100 k sample/sec with 24-bit resolution has been implemented. The data acquisition system is furthermore used for controlling the polarizer and mirror motors, etc as described in subsection 4.3.4).

During one week in August 2004 the upgraded collective Thomson scattering diagnostic system was successfully installed at the TEXTOR tokamak by a team from Risø and MIT with crucial assistance from colleagues from FOM and IPP (see Figure 60, Figure 61, Figure 62 and Figure 63). This upgrade included in-vessel access for welding and mounting of three mirrors, and subsequent alignment and mapping of the orientation of the in-vessel moveable mirror. The rest of the quasi-optical transmission line was also installed as well as the receiver electronics and the data acquisition system.

During a week in November/December 2004 a team from Risø commissioned the diagnostic, debugging the system hardware and software and adapting to communicate with the IPP (timing) and FOM (gyrotron) systems. The debugging of the software was done in remote collaboration with colleagues at Risø. Following the successful systems tests, ECE measurements were performed, while also tests of the motion of the antenna were successfully performed. Preliminary analysis of the ECE data seemed to be in correspondence with IPP's ECE diagnostics.

The system is now ready for CTS operations commissioning in early 2005 using the FOM gyrotron.

Figure 60. Most of the Risø and MIT team just before the installation in August 2004.

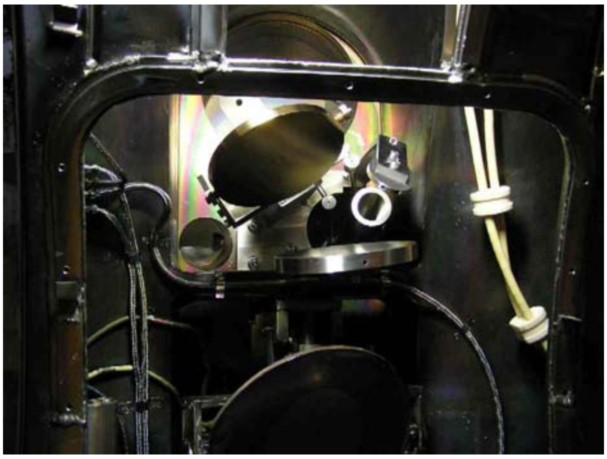

Figure 61. The CTS antenna mounted inside the TEXTOR vessel. The antenna consists of three mirrors, of which the top left one is moveable.

Figure 62. Work on the alignment of the quasi-optical transmission line.

Figure 63. The so-called wall plate with the universal polarizer and the receiver electronics (bronze coloured box). To the left is the cabinet with further electronics and the data acquisition system.

4.3.3 Alignment and test of the quasi-optical transmission line for the TEXTOR CTS

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The quasi-optical transmission line for the CTS system at TEXTOR contains seven mirrors, one universal polariser and a circular, corrugated waveguide. During 2004 this system has been aligned with a laser system in a test bed at Risø and the transmitted mm-waves have been measured. The transmission line can be divided into three parts. The first three mirrors are mounted inside the vessel, and the waveguide couples the beam from the in-vessel mirrors to the two mirrors sitting on the outside of the vessel. The last part of the system is mounted on a 1.2 m by 1.2 m plate on the wall in the torus hall. To test the system in the laboratory at Risø, a special holder to represent the vessel was produced. Figure 64 shows this set-up with mirrors 1 to 5 together with the antenna pattern measuring system (blue area).

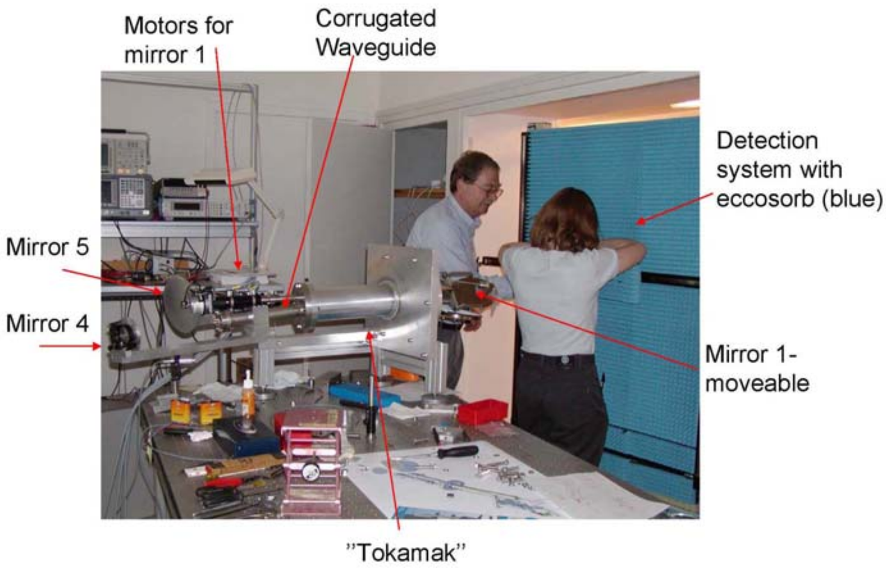

Figure 64. Alignment test.

The mm-wave beam has been successfully transmitted through the whole system from the receiver to mirror 1. Figure 65 shows the antenna pattern of the beam for one setting of mirror 1.

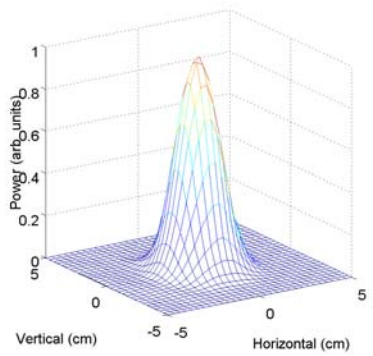

Figure 65. The antenna pattern of the beam for one setting of mirror 1.

During installation a different approach was needed since the measuring system was too large to fit into the tokamak. Instead the laser alignment was done, followed by optimisation of the mirror directions with either a cold or a hot source. This method relies on black body radiation in the mm-regime at different temperatures with respect to the radiation at room temperature. The hot source (heating element) was localised, but it had a smaller differential signal than the cold source (liquid N2). By placing the cold source in the vessel at a point localised by the laser, the mirrors were optimised so that the total loss in the transmission line was finally estimated to be approximately 2 dB. The main contribution to the loss is from the in-vessel to the out-vessel components.

We are currently building a mini-antenna pattern measuring system that can be put into the tokamak to test whether we can improve the alignment.

4.3.4 Acquisition and analysis software for collective Thomson scattering

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The acquisition of the CTS data at the TEXTOR and ASDEX experiment (see subsections 4.3.1 and 4.3.2) requires high bit resolution and fast scan rate from a hardware point of view and a flexible user interaction. The acquisition hardware situated at ASDEX consists of 56 ADCs located on seven NI-4472 cards while the TEXTOR system consists of six cards.

Each NI-4472 contains eight 100 ksamples/sec, 24 bits resolution adc-channels.

Each system has an additional NI-6040 card with 16 channels for miscellaneous use such as VCVA switch/attenuator control and automated temperature monitoring, see Figure 66. The software, written in Labview, has been updated substantially and now includes features such as polariser and mirror control. The full acquisition system has furthermore been commissioned successfully both at ASDEX and TEXTOR.

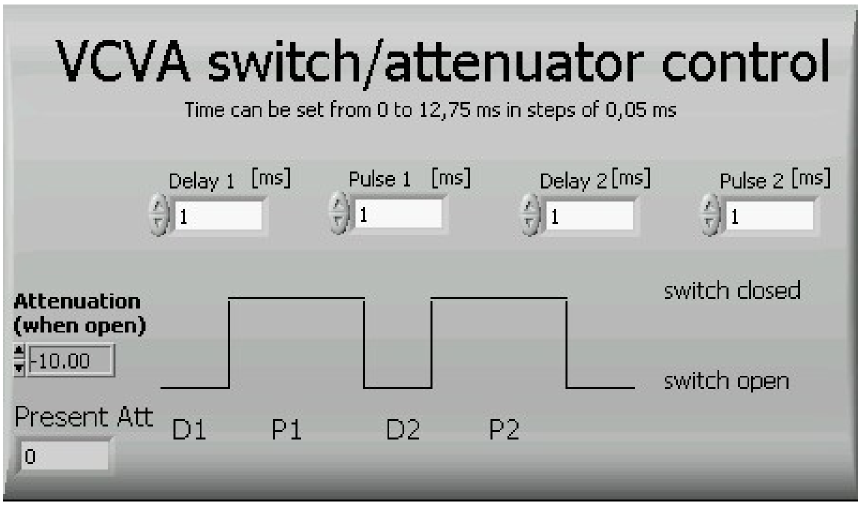

Figure 66. The VCVA switch/attenuator control in the RUDA program.

The basic function of the CTS data analysis package written for the pilot project calculates the fast ion distribution from the measured scattered radiation. It also analyses and optimises the scattering geometry to achieve optimal overlap. Keeping the core programs intact, a major upgrade to the manager routines has been made with the goal to create a generic environment to include the new data infrastructure of the pilot project as well as new CTS data, an environment that is portable to any operating systems running Matlab and FORTRAN.

4.3.5 Fast ion simulation

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The understanding of fast ion dynamics is of great importance in obtaining burning, magnetically confined fusion plasmas. The confinement of the energetic alpha particles created in the fusion processes is crucial since they need to heat the bulk plasma, see Figure 67.

A numerical code for fast calculations of guiding centre orbits of energetic ions in tokamaks has been developed. The code is based on first-order orbit theory and operates in constant of motion space (energy, magnetic moment and toroidal canonical momentum). The code will be the basis of a fast ion simulation, calculating the development in time of the fast ion distribution function due to slowing down by scattering off electrons and pitch angle scattering off ions.

Figure 67. Example of fast ion orbit in a fusion device.

4.3.6 Production of high quality quasi-optical mirrors at Risø National Laboratory

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Among the different microwave components of the receiver antenna of the collective Thomson ccattering (CTS) diagnostic system, the quasi-optical mirrors are one of key importance. Both CTS TEXTOR and CTS ASDEX Upgrade transmission lines consist of a number of mirrors of quasi-optical quality calculated, designed and manufactured at Risø.[1,2]

The whole procedure of the mirror production starting from an idea to its actual realisation is divided into several steps (Figure 68):

(a) At the beginning the problem is formulated in MatLab, where the whole transmission line is designed and optimised to meet the set requirements. The mirror *3D* surface is calculated and can typically be ellipsoidal or hyperboloidal in shape.

(b) Obtained numerical data of the mirror surface are transferred into the graphical design tool, CATIA, in order to finalise necessary engineering details.

(c) Data from CATIA are further transferred to the PC controlling the CNC cutting tools at the Risø workshop, where the mirror is cut from the metal.

(d) The surface of the produced mirror can be carefully analysed by the surface analyser also located at the Risø workshop and obtained data are sent back to the MatLab code, where a comparison between the measured data of the mirror surface and its corresponding theoretical value is performed.

The duration of all the steps of the mirror production from MatLab to metal may be several hours depending on the mirror shape, size and sort of metal being cut. Performance of the last (d) step shows that the difference between the theoretically calculated and the experimentally measured mirror surface is typically below the 1/10 of wavelength, demonstrating high quality of the produced mirror shapes.

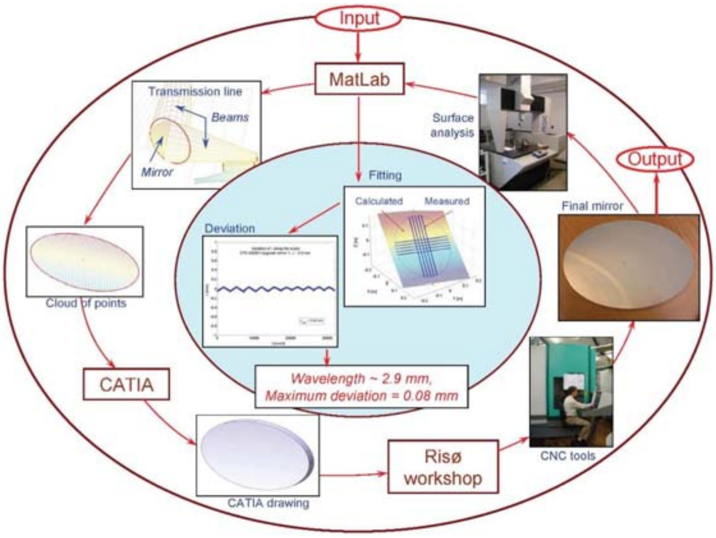

Figure 68. Production of the quasi-optical mirrors at Risø.

1. A.J.H. Donné, M.F.M. De Bock, I.G.J. Classen, M.G. Von Hellermann, K. Jakubowska, R. Jaspers, C.J. Barth, H.J. Van Der Meiden, T. Oyevaar, M.J. Van De Pol, S.K. Varshney, G. Bertschinger, W. Biel, C. Busch, K.-H. Finken, H.R. Koslowski, A. Krämer-Flecken, A. Kreter, Y. Liang, H. Oosterbeek, O. Zimmermann, G. Telesca, G. Verdoolaege, C.W. Domier, N.C. Luhmann, Jr., E. Mazzucato, T. Munsat, H. Park, M. Kantor, D. Kouprienko, A. Alexeev, S. Ohdachi, S. Korsholm, P. Woskov, H. Bindslev, F. Meo, P.K. Michelsen, S. Michelsen, S.K. Nielsen, E. Tsakadze, L. Shmaenok, "Overview of core diagnostics for TEXTOR", Fusion Science and Technology, TEXTOR special issue, **47**, n. 2, pp. 220-245, 2005.

2. S. Michelsen, S. B. Korsholm, H. Bindslev, F. Meo, P. K. Michelsen, E. L. Tsakadze, J. Egedal, P. Woskov, J. A. Hoekzema, F. Leuterer, E. Westerhof, "Fast ion millimeter wave collective Thomson scattering diagnostics on TEXTOR and ASDEX upgrades", Review of Scientific Instruments, **75**, n. 10, pp. 3634-3636, 2004.

4.3.7 Detailed integrated design of CTS for ITER

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The CTS system for ITER is based on a fixed antenna system to collect scattered microwaves from different toroidal positions in the tokamak. On the high field side the slap between two blanked modules shall work as the antenna. The collected signal is reflected by two mirrors into ten horns, one for each spatial position of the scattering volume. Work has been started to optimise the mirrors, the positions of the horns and the geometry of the slap. A finite difference approach is used to model the behaviour of the slap.

The model has a maximum resolution of 20 points per wavelength and a maximal number of points of 1600x800, limited by the large amount of physical memory needed for this task. Since there is no variation in the vertical direction of the set-up the problem can be decomposed into a number of 2D finite difference problems. It is assumed that the walls of the blankets are ideal conductors and therefore the boundary conditions are $\hat{n}\times\vec{E}=0$ and $\hat{n}\cdot\vec{H}=0$, where n is the normal, $\vec{E}$ is the total electric field vector and $\vec{H}$ is the total magnetic field vector. Furthermore, it is necessary to use a perfect matching layer to prevent standing waves in the solution, due to reflections on the edge of the computational area.

The calculated results will be compared with experimentally obtained data using realistic geometries. Figure 69 shows an example of the total electric field calculated for a Gaussian beam that is sent through a geometry illustrated by the yellow areas. The corners of the blanket modules have been rounded to decrease the reflection from the edge.

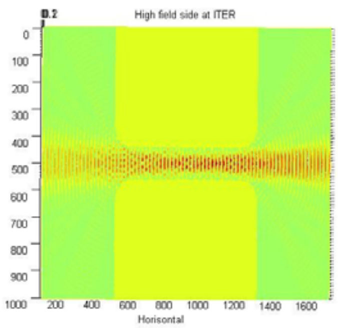

Figure 69. The total electric field is shown for the illustrated geometry (yellow areas).

4.4 Low temperature plasmas with environmental and industrial applications

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In low temperature plasmas, the electron temperature (a few tens of thousands of degrees) can differ greatly from the temperature of the ions and of the neutrals, which can be close to room temperature. Due to this low gas temperature, interaction of low temperature plasma with heat-sensitive material can be non-destructive. If, in addition, the plasma is operated at atmospheric pressure, process advantages generally ensue and expensive pumping and vacuum equipment is not required. This opens a wide field of industrial applications for low temperature plasma sources such as surface treatment, pollution remediation, and sterilisation.

4.4.1 Remediation of nitrogen oxide in the flue gas of a gas power plant

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This project seeks to develop a method for reducing the nitrogen oxide emissions from gas power plants by a plasma technique. Combustion of fossil fuel (in power plants or automotive engines) produces nitrogen oxides, commonly referred to as NO_x. NO_x causes acid rain and generates ozone. Effort thus needs to be put into reducing NO_x emission. We have tested injection of different reducing agents produced in an atmospheric pressure dielectric barrier discharge (DBD) into the synthetic exhaust gas as well as direct DBD treatment of the exhaust gas. A DBD consists of two electrodes with one or more layers of dielectric in between. We could not achieve efficient NO reduction by direct plasma treatment of synthetic exhaust gases containing oxygen.

As reducing agents we have injected NH_2 radicals and nitrogen atoms (N). The NH_2 radicals were produced in an Ar/NH_3 DBD plasma. A maximum NH_2 concentration was found for an NH_3 concentration between 6% and 8 %, but NH_2 was found to have a short life time (0.3 ns). Production of N_2H_4 (hydrazine) from NH_2 was detected by means of UV absorption spectroscopy in the discharge as well as downstream. Thermal dissociation of hydrazine into NH_2 radicals can support NO reduction but injection of hydrazine was found to be inefficient in reducing NO at temperatures up to 700^{o}C. N atoms generated in N_2 discharges have shown to decompose NO. Up to 75% NO reduction in a synthetic exhaust gas (N_2/NO mixture) was monitored by UV absorption spectroscopy and Fourier transform infrared (FTIR) spectroscopy. However, this requires high flow rates of N_2 through the discharge (six times the amount of exhaust gas), and NO reduction by injection of nitrogen atoms turned out to be too expensive.

The work is a collaborative project with participants from the Optics and Plasma Research Department, the Biosystems Department, both at Risø, and the Danish Gas Technology Center. This work is funded by the public service obligation (PSO) from Elkraft Systems (Order – 103159, FU 3401).

4.4.2 Atmospheric pressure plasma treatment of carbon fibres for adhesion improvement

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Carbon fibres exhibit high strength and modulus as well as high temperature resistance, and are regarded as one of the most important reinforcing materials. The mechanical properties of carbon fibre reinforced composites are highly dependent on the microstructure of the fibres, the fibre volume fraction and orientation as well as the performance of the fibre-matrix interface where the fibre and the matrix are chemically or mechanically connected.

This project attempts to develop atmospheric pressure plasmas for adhesion improvement of carbon fibres. A central milestone will be the development of an efficient surface modification of carbon fibres so that changes/improvements to the mechanical properties of carbon-fibre reinforced composites can be demonstrated.

Glassy carbon, consisting of graphitic crystallites plates with sizes close to those of carbon fibres, were chosen as model specimens of carbon fibres for fundamental studies of surface treatment, surface characterisation and mechanical testing. The glassy carbon plates were treated with atmospheric pressure plasmas generated between parallel-plate electrodes covered with alumina plates. Air and oxygen (O_2) gas were used as reactive gases. X-ray photoelectron spectroscopic (XPS) analysis showed that the oxygen content on the surface increased with O_2 plasma treatment, but decreased with air plasma treatments as shown in Table 1. It is therefore suggested that etching was pronounced with air plasma. Treated and untreated surfaces were reacted with epoxy at 110 ^{o}C for one hour, and the adhesion improvement was qualitatively examined. A peeling test of the treated glassy carbon covered with cured epoxy showed cohesive failure, indicating strong bonding after the treatments. This is in contrast to the peeling tests of untreated samples where the epoxy readily peeled off the glassy carbon. The activities will be continued in the new DanishTechnical Research Council project between the Optics and Plasma Research Department, the Danish Polymer Centre and the Materials Research Department, all at Risø, on the topic.

Table 1. Chemical composition of untreated and plasma treated glassy carbon surfaces characterised with XPS.

Sample	% C	% O	% N	%S
Untreated	82.5	17.3		0.2
Air plasma	86.3	12.6	0.9	0.2
O_2 plasma	77.8	19.0	1.7	1.6

4.4.3 Sterilisation by means of low temperature atmospheric pressure plasmas

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Sterilisation methods used at present (heat, moist heat, toxic substances, UV light, ionising radiation and low pressure plasmas) generally have one or more of the following disadvantages: (1) leave traces of toxic substances on or in treated objects, (2) require long treatment times, (3) use too high temperatures for heat-sensitive instruments, (4) limit the use of materials for medical equipment because of damage to material properties, (5) are cumbersome in use and (6) are expensive.

Exposure to chemical reactive species has been shown to destroy biologically active species.[1,2] In order to generate chemically reactive species, atmospheric pressure dielectric barrier discharges (DBDs) with parallel plate electrode geometry and coaxial electrode geometry have been developed. Alumina plates served as dielectric barriers. The discharge was generated in He/O_2 mixture as well as pure O_2. Samples of bacteria (E.Coli) and spores (Botrytis Cinerea) were exposed directly to the plasma (direct treatment) (E.Coli) or they were exposed to the exhaust gas of the discharge (remote treatment) (Botrytis Cinerea).

Exposure of *E.Coli* to plasma provides a reduction of five orders of magnitude within five minutes of treatment. The same results can be obtained by increasing the power reducing the exposure time to one minute. The evaluation was performed by growing treated and untreated bacteria on Petri dishes, see Figure 70.

One minute remote treatment of *Botrytis Cinerea* growing on a potato dextrose agar to a $N_2/O_2(3\%)/O_3$(200 ppm) provided by a DBD showed an inhibition in growth for up to18 h compared with untreated samples.

Figure 70. Bacteria of type *E. Coli* are growing on a nutrition solution in Petri dishes: a) untreated b) exposure time 1 minute, c) exposure time 5 minutes.

Sterilisation by means of low temperature atmospheric pressure plasmas has been demonstrated to be an alternative to conventional sterilisation techniques.

1. M. Laroussi, ”Nonthermal Decontamination of Biological Media by Atmospheric – Pressure Plasmas: Review, Analysis, and Prospects”, IEEE Trans. Plasma Sci., Vol. 30, No. 4, p. 1409 (2002).
2. M. Laroussi and F. Leipold, “Evaluation of the roles of reactive species, heat, and UV radiation in inactivation of bacterial cells by air plasmas at atmospheric pressure”, Int. J. of Mass Spectrometry **233**, p. 81 (2004).

4.4.4 Atmospheric pressure plasma treatment of polymers

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Surface modification of polymer surfaces to achieve either water (oil) repelling or water (oil) wetting properties is important for many technical applications such as the production of water-resistant clothes in the textile industry and improvement of printability of polymer materials in the publishing industry. Low-pressure plasma has been widely used for surface modification of semiconductors and polymers. However, in many practical applications treatment by atmospheric pressure plasmas is preferable.

Figure 71. Normal painted aquarelle paper before (left part) and after atmospheric pressure plasma treatment in Ar/C_3HF_7 mixture (right part).

The wettability of polymer surfaces can be improved by means of atmospheric pressure plasmas in air, oxygen or helium. However, in order to improve the water repellency of polymer surfaces more sophisticated methods are needed. Superior performances (for example, superhydrophobic coatings) can only be obtained using fluorocarbons as the active component in the carrier gas. Polymers were treated directly in an atmospheric pressure plasma and downstream of the plasma. Significant improvement of the water repellency was demonstrated. Direct treatment enables high deposition rates and improved stability and hardness of polymer films due to enhanced cross-linking. Still, soft coatings could be produced by downstream deposition. Figure 71 illustrates the effect of plasma treatment of painted aquarelle paper (cellulose based material).

5. Interdepartmental activities

5.1 Introduction

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In the following, joint scientific projects of the two research programmes *Laser Systems and Optical Materials* and *Optical Diagnostics and Information Processing* are presented.

5.1.1 Center for Biomedical Optics and New Laser Systems – BIOP

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www.biop.dk

The Center for Biomedical Optics and New Laser Systems (BIOP), established in 2000, is a Danish initiative where engineers, physicists, chemists and physicians collaborate on the development of new biomedical applications based on the most recent progress in lasers and optical measurement techniques. The aim of the centre is to conduct research and develop advanced laser systems and optical measurement technologies, and to apply these systems within dermatology, ophthalmology and biosensing.

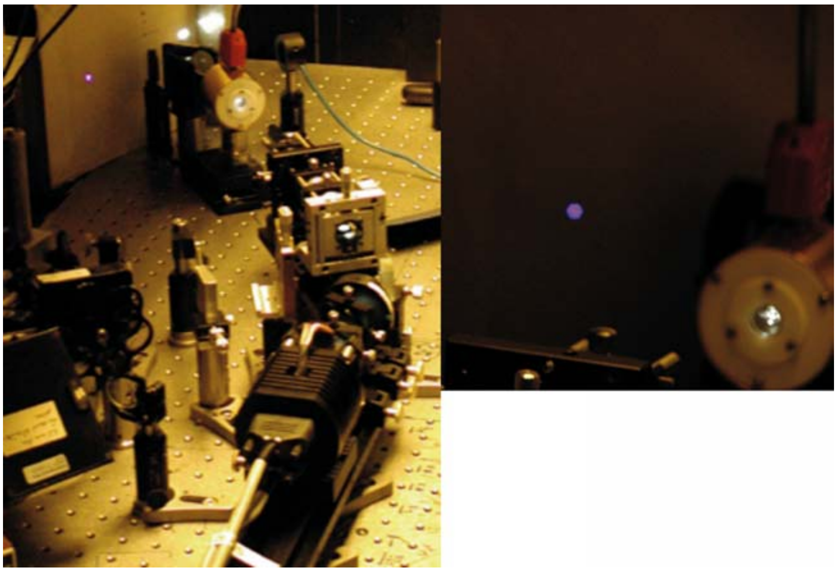

Figure 72. The laser running with single-pass frequency doubling in PP-KTP (405 nm out is viewed as the blue dot on the screen).

The main purpose of the BIOP research programme is to demonstrate and develop state-of-the-art diagnostic procedures as well as to improve therapeutic facilities at Danish hospitals. The collaboration has resulted in the development of novel biomedical applications of modern laser technology, including three-dimensional imaging in human tissue, blood flow visualisation, non-invasive spectroscopy and fluorescence measurements for diagnostics, and biosensors for measurements of concentrations of, e.g., glucose and protein. As an example, new frequency-lasers for diagnostics are developed, see Figure 72.

In the BIOP centre, five focus areas have been selected:

- Biomedical imaging systems
- New laser systems for diagnostic and therapeutic applications
- Optical tweezers systems
- Bio-sensing
- Biomedical image and data processing

Education in BIOP

Young scientists are offered coordinated training and education at undergraduate and PhD levels within the areas of laser technology, imaging, medicine and biotechnology through undergraduate courses and graduate schools, see also BIOP Graduate School. One of the objectives of this approach is that the education of PhD students takes place in close cooperation with the Danish business sector. The PhD projects carried out in BIOP are all structured as interinstitutional collaborative efforts. Moreover, permanently employed members of staff are given the possibilities of using facilities at other institutions and of participating in the education programme - an initiative that contributes to further strengthening of mobility.

Participants

Partners who hold strong positions in their own fields participate in BIOP. The following partners participate in BIOP:

- Department of Dermatology, Aarhus Amtssygehus, University of Aarhus
- Department of Mathematical Modelling, Technical University of Denmark
- Department of Ophthalmology, Herlev Hospital, University of Copenhagen
- Department of Physics, Technical University of Denmark
- Optics and Plasma Research Department, Risø National Laboratory
- Research Center COM, Technical University of Denmark

Located in the vicinity of Copenhagen, BIOP has strong collaboration with Lund Institute of Technology and Lund Medical Laser Centre, Lund (Sweden).

Another important aspect of BIOP is to establish collaboration with industrial partners through joint projects in which the developed technology is transferred to the industrial partner. Such collaborative projects may involve PhD students who participate in the research projects at the premises of the industrial partners as well as at the involved research institution.

5.1.2 BIOP Graduate School: "Biomedical Optics and New Laser Systems"

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The BIOP Graduate School: "Biomedical Optics and New Laser Systems" was formed under the BIOP centre, which is part of collaboration between the Technical University of Denmark and Risø National Laboratory. The graduate school received funding from the Danish Research Agency under grant no. 643-01-0092 for a three-year educational programme that started in August 2002. In June 2004, the school received an additional grant for co-financing three PhD-programmes. By October 2004, the total number of PhD-programmes funded by the school is ten.

The BIOP Graduate School is administered by the BIOP centre. The school is supervised by a board, which coincides with the board of the BIOP centre. Professor Preben Buchhave, Department of Physics, Technical University of Denmark, heads the graduate school and is also member of the board of the BIOP centre. The school board has appointed Peter E. Andersen from Risø National Laboratory school director along with a management team.

The purpose of the graduate school is to strengthen the educational efforts within the area of biomedical optics in Denmark emphasising the use of lasers and optical methods for diagnostics, manipulation and therapy. In this new interdisciplinary research area, the focus of the school will be on strengthening research activities and educational efforts and on enhancing collaboration between the fundamental physical and technical sciences and the medical, clinical and biological sciences.

Therefore, the graduate school supports PhD projects, conferences, graduate summer schools, visiting scientists and exchange students within the areas of the school.

Areas of the graduate school

The following list, which is not exhaustive, shows the main research and educational areas for the graduate school:

- Laser physics, laser technology and non-linear optics for biological and medical applications
- Inference based on mathematical processing of spatial and temporal structures
- Advanced data and image processing
- Optical sensors based on optical fibres and photonic crystal fibres for biological and medical applications
- Tissue optics and light propagation in tissue
- Optical excitation of biochemical processes
- Optical tweezers systems
- Lasers and optical methods for applications in ophthalmology
- Lasers and optical methods for applications in dermatology
- Lasers and optical methods for applications in cardiology

Graduate summer schools

In 2003, the first international graduate summer school "Bio-Photonics '03" was organised by Risø and Lund Institute and Technology taking place one week in June 2003. The initiative caught the eye of several international associations, see e.g. the list of co-sponsors, and SPIE profiled the event in their monthly magazine.[1] The success of this first graduate school in this field has spurred interest in organizing a series of graduate schools. Therefore, the second school in the series has been announced to take place in June 2005.

More information on the recent Bio-Photonics '03 and the forthcoming Bio-Photonics '05 can be found at:

- Bio-Photonics '03: www.biop.dk/biophot03/
- Bio-Photonics '05: www.biop.dk/biophotonics05

Figure 73. Steven Jacques, Oregon Medical Laser Center, answers questions from students between lectures at the school.

1. OE Magazine, published by the International Society for Optical Engineering, Oct. issue 2003, p. 30. http://oemagazine.com/fromTheMagazine/oct03/edu.html.

5.1.3 Bio-photonics: new lasers for diagnostic and therapeutic applications – BIOLASE

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The frame programme “Bio-photonics: new lasers for diagnostic and therapeutic applications – BIOLASE” is a collaboration between the Optics and Plasma Research Department at Risø National Laboratory, COM at the Technical University of Denmark, the company Crystal Fibre A/S and the Department of Dermatology at Roskilde University Hospital. BIOLASE is funded for a five-year period from the Danish Technical Research Council under grant no. 26-02-0020 and was initiated in 2003.

One major reason for the high current and rapidly increasing research activities in the field of bio-photonics is that optics inherently has the potential of providing non-invasive diagnostic and therapeutic procedures, which may lead to novel and improved methods. The aim of BIOLASE is to combine fundamental research in nonlinear optics and lasers to create novel laser systems and light sources for use in biomedical applications. The primary target is to develop laser systems for diagnostic purposes in collaboration with medical doctors, thus incorporating their needs and requirements at the earliest stage in the developmental process. The primary target for the clinical applications in BIOLASE is within the field of dermatology.

In the short term, BIOLASE will provide novel biomedical applications, such as ultrahigh-resolution imaging of skin tissue based on optical coherence tomography, fluorescence-based diagnosis of cancerous lesions and skin diseases, and new laser-based treatment procedures of skin cancer. The essential component to ensure such development is the light source. BIOLASE thus enhances research in advanced laser systems and light sources, and simultaneously points out new areas for applications of lasers. Furthermore, the programme also provides education of scientists highly specialised in optics, engineering and medical science.

In the long term, new diagnostic and therapeutic procedures will emerge from the joint efforts of the collaborators. Hence, the interdisciplinary collaboration provides a firm basis for transferring results from basic research to applications, which is emphasised by the participation of the Danish company Crystal Fibre A/S.

6. Publications

6.1 Laser systems and optical materials

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Andersen, P.E., Biomedical non-invasive imaging techniques. Slutrapport for projekt 9901433. Risø-Dok-768 (2004) 11 p.

6.3 Plasma physics and technology

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7. Personnel

Head of department

Jens-Peter Lynov

Heads of research programmes

Henrik Bindslev, Plasma Physics and Technology
Hanson, Steen Grüner, Optical Diagnostics and Information Processing (until 31 August)
Pedersen, Christian, Optical Diagnostics and Information Processing (from 1 September)
Petersen, Paul Michael, Laser Systems and Optical Materials

Scientific staff

Andersen, Peter E.
Bak, Jimmy
Clausen, Sønnik
Dam-Hansen, Carsten
Daria, Vincent (until 31 October)
Fateev, Alexander
Glückstad, Jesper
Hansen, René Skov
Hanson, Steen Grüner
Jakobsen, Michael Linde
Johansen, Per Michael (until 31 December)
Jørgensen, Thomas Martini
Kirkegaard, Mogens
Korsholm, Søren B. (from 1 December)
Kusano, Yukihiro
Larsen, Henning
Leipold, Frank
Michelsen, Poul K.
Naulin, Volker
Nielsen, Anders H.
Nielsen, Birgitte Thestrup
Pedersen, Henrik Chresten
Ramanujam, P.S.
Rasmussen, Jens Juul
Schou, Jørgen
Stenum, Bjarne
Thrane, Lars

Post Docs

Chi, Mingjun
Christensen, Bo Toftmann (1 June- 30 November)
Friderichsen, Anders (until 31 March)
Garcia, Odd Erik
Horvath, Robert
Kasimova, Marina
Korsholm, Søren B. (until 30 November)

Michelsen, Susanne
Meo, Fernando
Nedelchev, Lian (5 July – 30 November)
Pedersen, Christian (until 31 August)
Perch-Nielsen, Ivan (from 1 June)
Tsakadze, Erekle
Vienne, Guillaume (1 May – 31 July)

Technical staff

Andersen, Finn
Begovic, Tanja
Eliasen, Finn
Holm, John
Falsvig, Erik
Jessen, Martin
Knudsen, Lene (until 31 October)
Nielsen, Karsten Lindorff
Nimb, Søren
Nordskov, Arne
Pedersen, Finn
Pedersen, Søren Peo
Petersen, Torben D. (until 31 December)
Rasmussen, Erling (until 31 August)
Sass, Bjarne
Stubager, Jørgen
Thorsen, Jess

Administrative staff

Andersen, Heidi (until 31 March)
Astradsson, Lone
Schwartzbach, Camilla (from 8 March)
Skaarup, Bitten

Research assistant

Rasmussen, Inge (6 September – 31 October)

Laboratory assistant

Bülow, Jon Fold von

PhD students

Andersen, Eva Samsøe
Apitz, Dirk
Christensen, Bo Toftman (until 31 May)
Falk, Peter
Frosz, Michael
Holm, Jesper
Kristensen, Peter Kjær
Nielsen, Frederik Donbæk

Nielsen, Stefan Kragh
Nikolov, Nikola Ivanov (until 28 February)
Rodrigo, Peter John
Senchenko, Sergey (until 31 March)
Skivesen, Nina
Sørensen, Henrik Schiøtt

Marie Curie student

Janik, Katarzyna (until 30 April)
Kramer, Werner (1 March – 1 September)

MSc students

Andersen, Grith Hougaard (until 31 July)
Bjernemose, Keld (until 7 April)
Correia, Teresa (14 June – 31 December)
Dirksen, Kim (until 30 June)
Fruelund, Morten (from 6 February)
Gualdino, Alexandra (14 June – 31 December)
Haghighi, Navid (until 16 January)
Lentge, Heidi (until 31 May)
Levitz, David (until 15 June)
Mousavian, Shabab (until 16 January)
Nielsen, Thomas Nørskov (2 February – 1 June)
Sanz, Laura Pastor (until 31 March)
Torp, Anders (1 March – 31 August)
Wood, Martin Priego (16 February – 1 August)

BSc students

Becker-Olsen, Rune (24 May – 11 December)
Damkjær, Sidsel Marie Skov (16 March – 1 July)
Jørgensen, Kenneth (from 31 August)
Kristensen, Dennis Karsten (5 January – 9 July)
Koksø, Maja (from 1 December)
Nilsson, Ronnie Thorup (until 31 May)
Pejrup, Christian (from 1 October)
Rune, Henrik (from 13 September)
Samardzic, Semir (from 20 September)

Visiting students

Alonzo, Carlo Amadeo (2 November – 13 December)
Benter, Niels (13 july – 31 October)
Gauffny, Francois-Xavier
Komorowska, Katarzyna (16 November – 30 November)
Latham, Joey Clinton (18 August – 18 November)
Levitz, David

Nielsen, Thomas Nørskov (1 April- 15 June)
Rodrigo, Katarzyna (1 June- 31 December)

Student assistants

Gavnholt, Jeppe (28 June – 3 September)
Jacobsen, Lærke Bang (5 July – 16 September)
Jalgar, Madhukeswara (5 July - 15 September)
Pedersen, Johan Rønby (1 July – 31 August)
Thomadsen, Jakob (5 July – 13 August)

Guest scientists and short-term visitors

Bornhop, Darryl, Vanderbilt University, USA
Bruhns, Hardo, Euratom, Brussels, Belgium
Foster, Florian, Lund Institute of Technology, Sweden
Fundamenski, Wojtek, UKAEA, Culham, United Kingdom
Grauer, Rainer, Ruhr-Universität Bochum, Germany
Grulke, Olaf, Max Planck Inst. Plasma Physics, Greifswald, Germany
Hesthaven, Jan, Brown University, USA
Jaiman, N.K., Physics Department, Raj Rishi College, University of Rajasthan, India
Janeschitz, Günther, FZK, Karlsruhe, Germany
Kats, Alexander, University of Kharkov, Ukraine
Köppe-Bindslev, Britta, Amtssygehuset i Glostrup, Glostrup, Denmark
Pamela, Jerome, EFDA-JET, CSU Culham, United Kingdom
Pésceli, Hans, University of Oslo, Norway
Podivilov, Evgeny, Institute of Automation and Electrometry, Novosibirsk, Russia
Ratynskaya, Svetlana, IPP Garching, Germany
Reboud, Vincent, Lab. Charles Fabry de l'Institut d'Optique, CNRS, Orsay, France
Rypdal, Kristoffer, University of Tromsø, Norway
Woskov, Paul P., Massachusetts Institute of Technology, Cambridge, USA
Yura, Hal, The Aerospace Corporation, Los Angeles, USA

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Abstract (max. 2000 characters)

The Optics and Plasma Research Department performs basic and applied research within three scientific programmes: (1) laser systems and optical materials, (2) optical diagnostics and information processing and (3) plasma physics and technology. The department has core competencies in optical sensors, optical materials, biophotonics, fusion plasma physics, and industrial plasma technology. The department employs key technologies in micro- and nanotechnology for optical systems, temperature calibration, and infrared measurement techniques. The research is supported by several EU programmes, including EURATOM, by Danish research councils and by industry. A summary of the activities in 2004 is presented.

Descriptors INIS/EDB

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